2007-09

Ground segment preparation for NPSAT1

Koerschner, Luke E.

Monterey, California. Naval Postgraduate School

http://hdl.handle.net/10945/3261

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

GROUND SEGMENT PREPARATION FOR NPSAT1

by

Luke Koerschner

September 2007

Thesis Advisor:	James A. Horning
Second Reader:	David Rigmaiden

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2007	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE Ground Segment Preparation for NPSAT1			**5. FUNDING NUMBERS**
6. AUTHOR(S) Luke Koerschner			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

Most satellites rely on a ground control station to command their payloads and through which they download data from their payloads. The Naval Postgraduate School's satellite (NPSAT1) is no exception. The spacecraft's payloads, which include the Coherent Electromagnetic Radio Tomography (CERTO), Langmuir probe, Configurable Fault Tolerant Processor (CFTP), as well as the Visible Wavelength Imager (VISIM), all generate data that require collection on the ground through a radio frequency downlink. Telemetry from NPSAT1's unique attitude control system, which uses only MEMS angular rate sensors, magnetic coils, a magnetometer and a GPS could aid in the development of improved or more economical attitude control systems. The goal of this thesis is to ready the ground control segment for operation for collection of data from and command of NPSAT1 immediately after launch.

Included is a description of the spacecraft to ground calculation, bidirectional, link budget and the operation and testing of the ground antenna pointing control system. Future space systems students and faculty will use the ground control segment to harvest the data and reap the knowledge of the experiments that will orbit inside NPSAT1. What better way to test the pointing of the antenna than to use it to track the Midshipman Space Technology Applications Research Program's first satellite (MidSTAR1).

14. SUBJECT TERMS Ground Segment, NPSAT1, MidSTAR1			**15. NUMBER OF PAGES** 77
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

GROUND SEGMENT PREPARATION FOR NPSAT1

Luke E. Koerschner
Major, United States Army
B.S., North Carolina State University, 1990

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SPACE SYSTEMS OPERATIONS

from the

NAVAL POSTGRADUATE SCHOOL
September 2007

Author: Luke Koerschner

Approved by: James A. Horning
Thesis Advisor

David Rigmaiden
Second Reader

Professor Rudolf Panholzer
Chairman, Space Systems Academic Group

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Most satellites rely on a ground control station to command their payloads and through which they download data from their payloads. The Naval Postgraduate School's satellite (NPSAT1) is no exception. The spacecraft's payloads, which include the Coherent Electromagnetic Radio Tomography (CERTO), Langmuir probe, Configurable Fault Tolerant Processor (CFTP), as well as the Visible Wavelength Imager (VISIM), all generate data that require collection on the ground through a radio frequency downlink. Telemetry from NPSAT1's unique attitude control system, which uses only MEMS angular rate sensors, magnetic coils, a magnetometer and a GPS could aid in the development of improved or more economical attitude control systems. The goal of this thesis is to ready the ground control segment for operation for collection of data from and command of NPSAT1 immediately after launch.

Included is a description of the spacecraft to ground calculation, bidirectional, link budget and the operation and testing of the ground antenna pointing control system. Future space systems students and faculty will use the ground control segment to harvest the data and reap the knowledge of the experiments that will orbit inside NPSAT1. What better way to test the pointing of the antenna than to use it to track the Midshipman Space Technology Applications Research Program's first satellite (MidSTAR1).

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to thank my second reader, David Rigmaiden, for the hands on work that he did to make the antenna setup a reality. Thanks also to Professor Billy Smith of the U.S. Naval Academy for his invaluable assistance. The morning he spent showing me his ground control segment saved me weeks of work with the Nova software. LTC Lawrence Halbach directed my initial self directed study of the ground segment. Glenn Harrell's work machining the feed horn mount and creating a measurement tool to check that the feed horn was in the center of the parabolic dish was much appreciated. Dr. James Newman had the idea of using an anemometer to park the antenna in the safe position during periods of high winds allowing us to use a commercial ballast mount. I would also like to thank Mr. David G. Brinker P.E., S.E. of the Rohn Products Division of Radian Communications Services Inc. for permitting me to publish Rohn figures in this thesis. MAJ Steve Moseley mounted the feed horn cover. Professor Rudolph Panholzer suggested moving the azimuth motor lower and closer to the ballast mount to improve stability following azimuth changes. Finally I would like to thank my thesis advisor, Jim Horning, for the software scripts he wrote for my thesis work with the controller and for his tireless proofreading of this thesis.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. STATEMENT OF THE PROBLEM

Most communications satellites are in geostationary (GEO) orbit allowing terrestrial transmitters and receivers to point their antennas to fixed elevation and azimuths indefinitely. Other military dishes are designed to track geosynchronous satellites by dithering toward the strongest signal strength to follow the minor changes in azimuth and elevation of their geosynchronous target. Many low earth orbiting (LEO) satellites relay data to GEO satellites which pass that information down to terrestrial receivers. NPSAT1 is a LEO satellite without the benefit of a relay satellite. Data from NPSAT1 experiments will only be available if telemetry can be requested and received by a ground segment. The ground antenna’s four degree spot beam will require a high degree of pointing accuracy from the controller. Other considerations arise from a student satellite with a finite design life. With a limited lifespan it is desirable to establish communications with the satellite immediately after launch; ideally the ground control segment should be fully operational prior to launch.

B. NPSAT1 OVERVIEW

The student and faculty built NPSAT1 is a LEO satellite which is designed to be a secondary payload on a military or government launch. It incorporates an Evolved Expendable launch vehicle Secondary Payload Adapter (ESPA) for mounting as a secondary payload under the Orbital Express primary payload which was to be launched on an Atlas V rocket. That launch was missed, so arrangements are being made to launch in 2009 on a Minotaur rocket with an ESPA secondary payload suite. NPSAT1 uses commercial, off the shelf, lithium ion batteries. The cylindrical polygon shape of NPSAT1 has solar panels mounted on each of its twelve faces, and will incorporate on orbit testing of a triple junction solar cell design. The telemetry and command patch antenna design is described in detail by Erel (2002). Testing of these microstrip antennas was documented by Gokben (2003). Two sets of transmit and receive antennas are found

on the satellite. The primary transmit/receive (TX/RX) antennas are on the nadir pointing side of the satellite and the back up antennas are on the zenith pointing side. The transmit antenna is an elliptical patch measuring 5.66 cm across the short axis and 6.6 cm across the long axis. The receive antenna is a larger elliptical patch measuring 7.293 cm across the short axis and 8.509 cm across the long axis. Naval Research Laboratory (NRL) experimental payloads include the coherent electromagnetic radio tomography (CERTO), and a Langmuir probe. Naval Postgraduate School (NPS) experiments consist of a three axis micro-electromechanical (MEMS) rate sensor combined with magnetic coils to implement a magnetic attitude control test and a visible wavelength imager (VISM). The Solar cell Measurement System (SMS) experiment will test the new solar cell technology that will orbit on the satellite. Additionally, the CFTP is a Naval Postgraduate School (NPS) designed payload that will orbit on NPSAT1. A CFTP is currently in use on MidSTAR1. Results from MidSTAR1 telemetry show that the CFPT is experiencing single event upsets over the South Atlantic Anomaly (SAA) region. The SAA is a region in space over Brazil where the magnetosphere has a decrease in strength. The magnetosphere protects the Earth and LEO spacecraft from most solar high energy radiation particles which are strong enough to change a bit in a processor. More in depth reports of the CFTP voting circuit operation will be included in NPSAT1 telemetry.

II. NPSAT1 GROUND SEGMENT OVERVIEW

A. GENERAL

The ground segment consists of those components on the ground that allow control of and communications with the spacecraft. The NPSAT1 ground segment includes a 10 foot parabolic dish antenna which is operated through a general purpose computer that sends commands to the controller which steps the azimuth/elevation motors. The uplink to NPSAT1, and downlink from it are handled with two frequencies and those signals are passed through a modulator/demodulator (MODEM) between the computer and the antenna. An overview of the ground segments components is depicted in Figure 3. This section covers components of the ground segment in more detail.

1. Frequencies

A single ground relay antenna is used to transmit to the NPSAT1 at 1767.565 MHz L-Band and receive transmissions from NPSAT1 at 2207.3 MHz S-band. Doppler shift is compensated for in the high and low frequency synthesizers. The separation of these two frequencies allows full duplex communications without interference between the two frequencies.

2. NPSAT1 Antennas and Pointing

Communications with NPSAT1 is not contingent upon the proper functioning of its Attitude Control Subsystem (ACS). Normally the ACS keeps transmit and receive antennas pointed toward nadir. The zenith pointing antennas act as a backup to the Nadir pointing antennas in the event the spacecraft looses pointing capability and begins to tumble. The tolerance of NPSAT1's nadir pointing via its ACS is estimated to be +/- 10 degrees. NPSAT1 uses hemispherical patch antennas with half power beam widths determined by Erel (2002) to vary between 60.1 and 79.5 degrees at the uplink frequency and between 65.6 and 74.3 degrees at the downlink frequency (p. 42, 46). The average uplink half power beam width is 69.8 degrees, and the downlink average beam width is

69.5 degrees. The fact that they are omni directional allows them to transmit and received at much wider beam widths if the link is strong enough. For the purpose of calculating the link budget the rounded average beam width of 70 degrees was used for both uplink and downlink from NPSAT1.

NPSAT1's sister satellite MidSTAR1, which was built for Naval Academy payloads, also contains a CFTP that was designed at NPS. The same design will be employed on NPSAT1. MidSTAR1 does not have an attitude control system so it experiences roll fades. A roll fade is a drop in radio frequency signal strength that occurs when the satellite rolls from one omni directional antenna to another. Roll fades on MidSTAR1 can cause the temporary loss of communications when combined with pointing error losses. This is mentioned because NPSAT1 will also experience roll fades if its attitude control system fails. NPSAT1's attitude control system points it to nadir not directly toward the ground antenna. As a result of the nadir pointing antenna on NPSAT1 fades in signal strength will be experienced at low elevation angles even when the attitude control system is working. These fades can occur because the antennas on NPSAT1 will not always have the ground antenna in their half power beam width. This concept of "horizon fade" is best understood by Figure 1 which is conceptual and obviously not drawn to scale, because the four degree spot beam has an arc length of 149 km at 10 degrees of elevation.

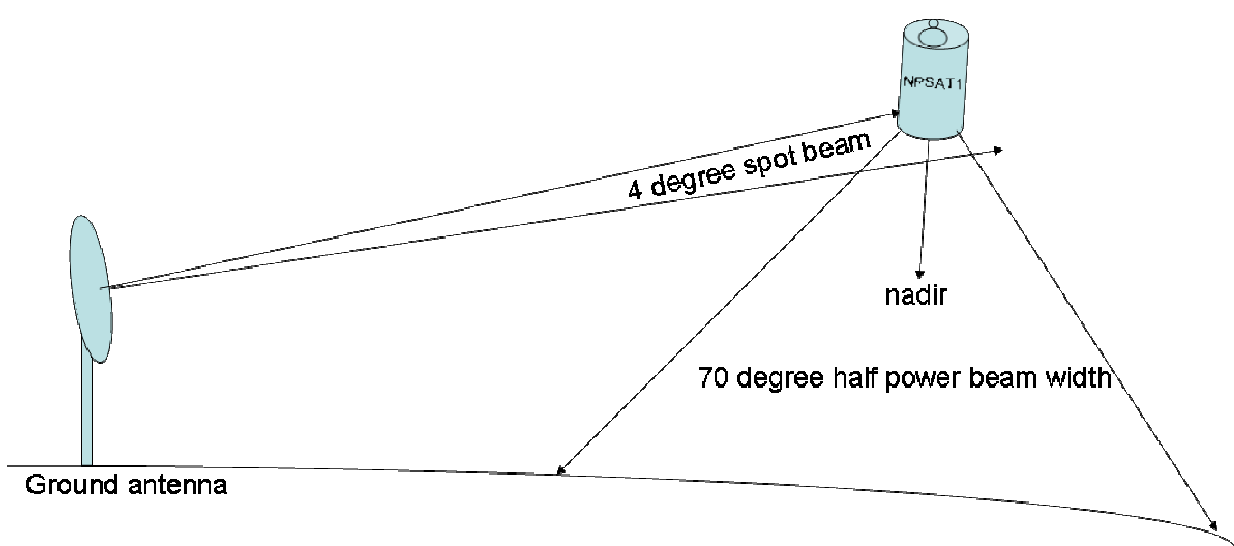

Figure 1. Horizon Fade

3. NPSAT1 Passes

Depending on the inclination of the spacecraft's orbit there should be at least four good opportunities to communicate with NPSAT1 each day. The original launch inclination would have yielded four daily satellite ground passes high enough above the horizon to permit time for downlink and uplink. Professor Smith of the Naval Academy has had good success with low grazing passes too, and if transmission and reception initiates below 10 degrees elevation then the system may have six usable passes daily. Presently MidSTAR1's orbit offers six good passes a day. Since MidSTAR1 has an inclination higher than the latitude in Monterey, CA it can pass directly over, or to the North of, the antenna at NPS. Those passes may be associated with loss of connectivity near zenith as the azimuth is changing faster than the antenna controller can receive commands and send status updates to the computer. This topic is discussed in more detail in this chapter (Section B3).

B. COMMAND PATH (UPLINK AND DOWNLINK)

1. Computer and Software

One software component of the computer is the orbit propagator. Since orbital ephemeris is only down linked once a day, software must predict the satellite's position over time with mathematical algorithms. The propagator that was tested for this thesis was embedded in Northern Lights Software's Nova program. Satellite Toolkit (STK) was also used to propagate orbital data in early tests that used software written for an operating system shell to send commands to the controller. Both propagators worked well but the Nova software communicates directly to the controller while STK requires that the pertinent orbital data be exported and requires more programming.

The computer with propagation software relays to the modulator de-modulator (MODEM) which mixes the intermediate frequency with the carrier frequency and feeds that communications signal through the low frequency synthesizer. The communications signal is sent back through the modem and out the antenna. Similarly signals received from NPSAT1 are sent through the MODEM to the high frequency synthesizer which

sends the signal back to the modem and on to the computer. Figure 2 illustrates the mixing of the intermediate frequency with the local oscillator for modulating the uplink frequency.

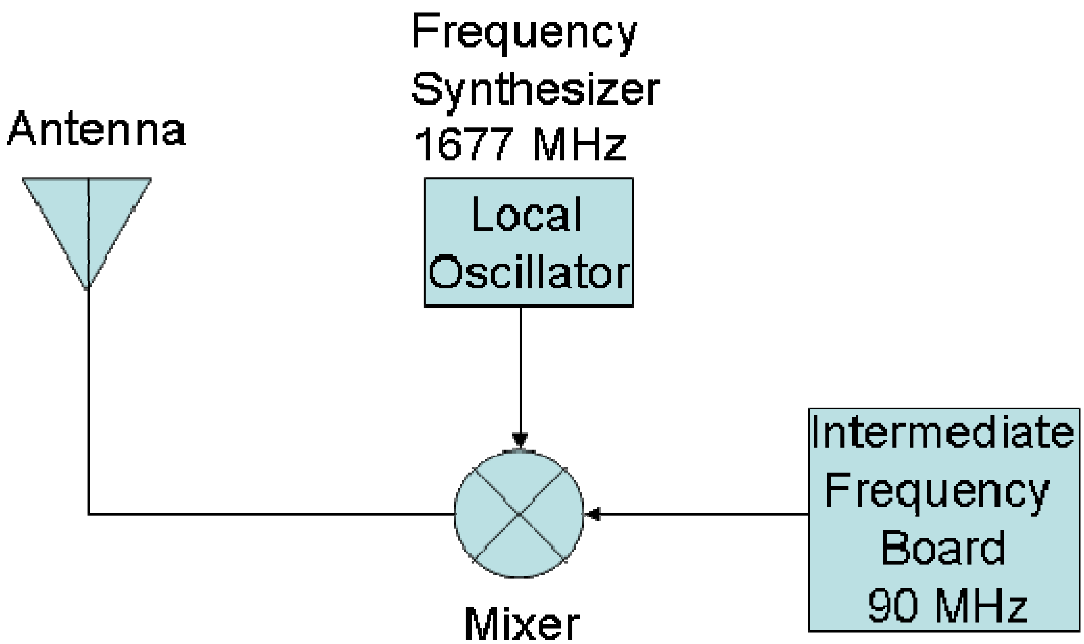

Figure 2. Uplink Frequency Mixing

Similarly the downlink frequency will be demodulated in a L3 software radio card that is on order. The L3 digital TT&C will eliminate the stand alone high frequency synthesizer from the architecture as will be described in this chapter (Section B2). Both synthesizers account for the Doppler shift of the moving satellite through programmed step routines. Doppler shift, the apparent increase in radio frequency of transmissions from an ascending satellite as it approaches the ground antenna and decrease in radio frequency of the frequency of the same transmissions from the satellite on its decent, is significant given the high velocities of spacecraft in the LEO regime.

Other inputs to the computer include the weather station and may also include a digital camera, and a GPS. The weather station signals will send data to the computer through a serial port. The weather station signal of interest is the wind speed which will, in high winds, alert the computer to command the controller to elevate the dish antenna to a safe position. Digital cameras could be affixed to the antenna to provide visual

feedback to a remote computer being used to control the antenna over the campus network. The UHF antenna that was used for a previous NPS-built satellite had a light-sensitive diode mounted on it that allowed the ground controller to bore sight its Yagi-Uda antennas with the Sun. A GPS could be connected to the computer to keep the computer time synchronized with GPS time and consequently the satellite's ephemeris time.

The computer is the nerve center of the entire ground communications system. It is an Intel® Core™ 2 CPU 6300 @ 1.86G Hz 1.86 GHz with 1 GB of RAM. It was ordered with multiple PCI card slots to accommodate the L3 communications card on order as well as the PCI card that allows it to connect to the Frequency Synthesizer. The current setup uses Northern Lights Nova software to communicate through a single serial cable to a M^2 RC2800PRK dual rack mount controller. The controller is described in this chapter, this section, number 3.

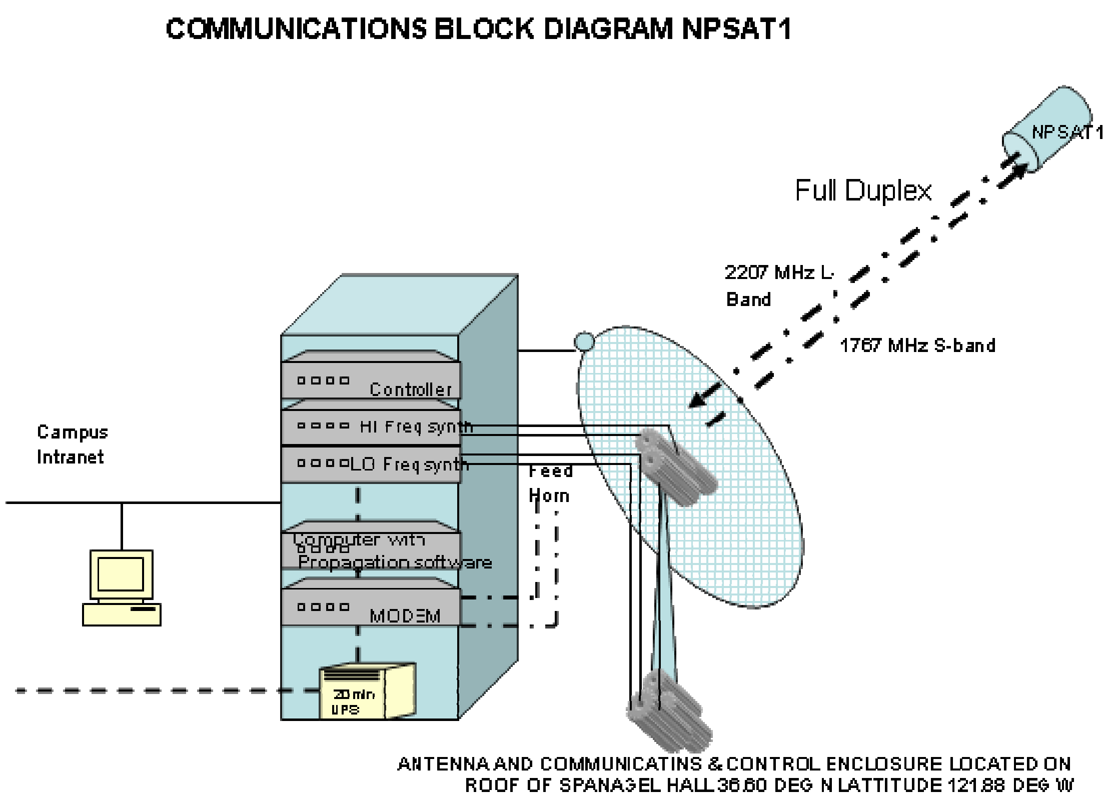

Figure 3. Communications Block Diagram NPSAT1

2. Digital Telemetry Receiver with Tracking

Delivery of the L3 Communications PCI-2070 Digital Telemetry Receiver with Tracking is not anticipated until after this thesis is written, but its capabilities will be discussed here. The L3 Technical Bulletin (2004) states the following:

> Capable of accepting RF input signals from -10 dBm to -70dBm, the PCI-2070 will receive the RF signal, condition and digitally demodulate FM, FSK, PM, BPSK, QPSK, OQPSK data. The image frequency bandwidth is programmable from 50 kHz to 30 MHz. The AFC (auto frequency control) tracking feature compensates for Doppler shift and other transmitter anomalies by using DSP algorithms to determine if the input spectrum is centered at the programmed center frequency. If the input spectrum is not symmetrical, the digital down converter is automatically stepped to track the input frequency.

One of the biggest advantages of this digital telemetry receiver card is its tracking capability which allows it to automatically compensate for Doppler shift with its automatic frequency control (AFC). This card will eliminate the need for the high frequency synthesizer depicted in Figure 3.

The card uses a Phase Lock Loop (PLL) in conjunction with Digital Signal Processing (DSP). The phase lock loop uses one or more traditional analog oscillators in combination with DSP. This card does not use Direct Digital Synthesis (DDS) in which the oscillator waveforms are generated in a processor. Some advantages of combining PLL technology with DSP is that the card is smaller and better at reducing spurious signals. Another advantage of this hybrid signal processing card is that its clock speed does not have to be multiples faster than the frequency of the generated waveform as is required in DDS. With a true DDS card, the clock speed of its processor would have to be at least twice the frequency because as described by Reed (2002) "The Nyquist sampling theorem limits the theoretical maximum attainable output lowpass frequency to half the clock frequency…" (p. 131). It is more likely that the clock speed of a comparable DDS card processor would have to be approximately 7 GHz (1.76 GHz (4)) because Reed (2002) states "it is customary to limit Δr to $F_{clk}/4$ to accommodate non-ideal analog filters." (p. 135). Δr represents a frequency word. Essentially a DDS card of equal

capability would have to have a much larger processor that would consume more power, and radiate more heat, than the computer's two 1.86 GHz CPUs. The interface of the card to the PC is via a PCI slot using a 32 bit PCI form factor.

3. Controller

The controller sends signals to two electric motors one for azimuth and the other for elevation. The controller pans across the heavens based on an open loop control scheme for elevation and azimuth of the dish antenna. In other words, once the elevation and azimuth are set off of a known point or celestial object the antenna may drift from those settings. The Naval Academy used the sun as the reference point for their antenna and they reset their azimuth and elevation calibration before every pass when possible. The motors send feedback to the controller for a closed loop control scheme. The controller has the antenna follow the predicted path of NPSAT1 during an overhead pass. One drawback of the Dual Rack mount controller is that it has a single 9600 baud serial port connection which has to receive separate commands for azimuth and elevation changes. The fastest update rate that can be used between the Nova software running on the computer and the controller is one second. Setting the update rate faster than that could result in the dropping of commands by the controller. Dropping commands occurs when the controller receives commands faster than it can execute them and subsequent commands are sent before the previous command has been executed, so commands are "dropped" by the controller. The RC2800PX/AZ and the RC2800PX/EL controllers were also purchased as spares. They allow the option of switching to separate elevation and azimuth controllers with individual serial port connections. Although the computer only has one 9-pin serial port, a USB port to serial cable adapter was tested with HyperTerminal to demonstrate that separate azimuth and elevation serial connections could be used. If separate controllers are used the CPU will have to send commands to both of them simultaneously through multiple RS-232 serial connection achieving more responsive antenna control. The connections to the dual rack mount controller are shown

below in Figure 4. The black and white wires are connections to the azimuth and elevation motors and the orange and blue wires connect to the pulse switches which give motion feedback to the controller.

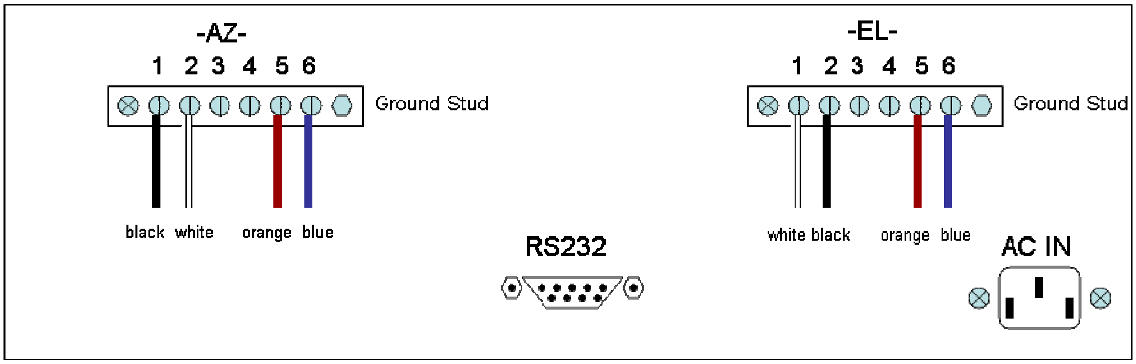

Figure 4. Connections on back of RC2800 PRK Dual Rack Mount Controller

4. Ground Antenna

A mesh parabolic ground antenna is located on the roof of Spanagel Hall (8th floor) at the Naval Postgraduate School in Monterey, CA. 36.595 degree North Latitude by 121.875 degree West Latitude. Figure 5 is a sketch of the location of the antenna in relation to other equipment on that deck.

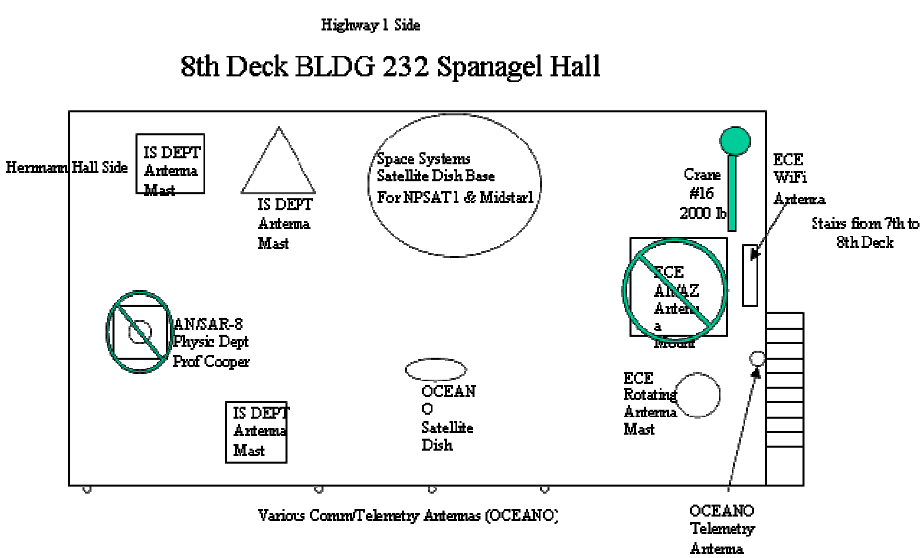

Figure 5. Antenna Deck Spanagel Hall

The uplink beam width of the ground antenna is approximately four degrees and is a function of the frequency and antenna diameter. The ground antenna’s downlink beam width is approximately three degrees. The pointing accuracy of the ground antenna must be less than or equal to two and a half degrees to maintain the down link as will be discussed in Chapter III. A two and a half degree error translates into an error arc length of 24 kilometers while pointing at NPSAT1 560 km directly overhead. The maximum path loss is 162.7 dB on the uplink and 164.6 dB on the downlink as will be calculated in Chapter III. The antenna is a 3.048 meter (10 feet) parabolic dish type reflector. The antenna reflects signals transmitted from NPSAT1 onto the feed horn. The feed horn also radiates the parabolic reflector with signals transmitted to NPSAT1. A minimum transmit elevation over land of 10 degrees may be used to mitigate the chance of interfering with ground receivers. Over the Monterey Bay it should be safe to transmit and receive at zero degrees elevation because there are fewer ship borne transmitters and receivers that are at risk of interference on the bay than on land.

An antenna limitation is that it cannot slew through more than 374 degrees of azimuth (14 degrees of overlap) or more than 90 degrees of elevation. Because of these limitations the antenna will not be able to continuously follow a satellite that passes directly overhead. Once the elevation of the antenna reaches 90 degrees the antenna would have to rotate through 180 degrees of azimuth before following the satellite as it descended on the through the eastern horizon. The time required to rotate would result in a temporary loss of connectivity. Antennas that have to be slewed at their maximum elevation to follow the satellite on its descending pass are said to have a “keyhole” in Air Force jargon because one has to turn the antenna just like a key. Figure 6 is helpful in visualizing this keyhole where the antenna azimuth has to be rotated once the maximum dish elevation is reached.

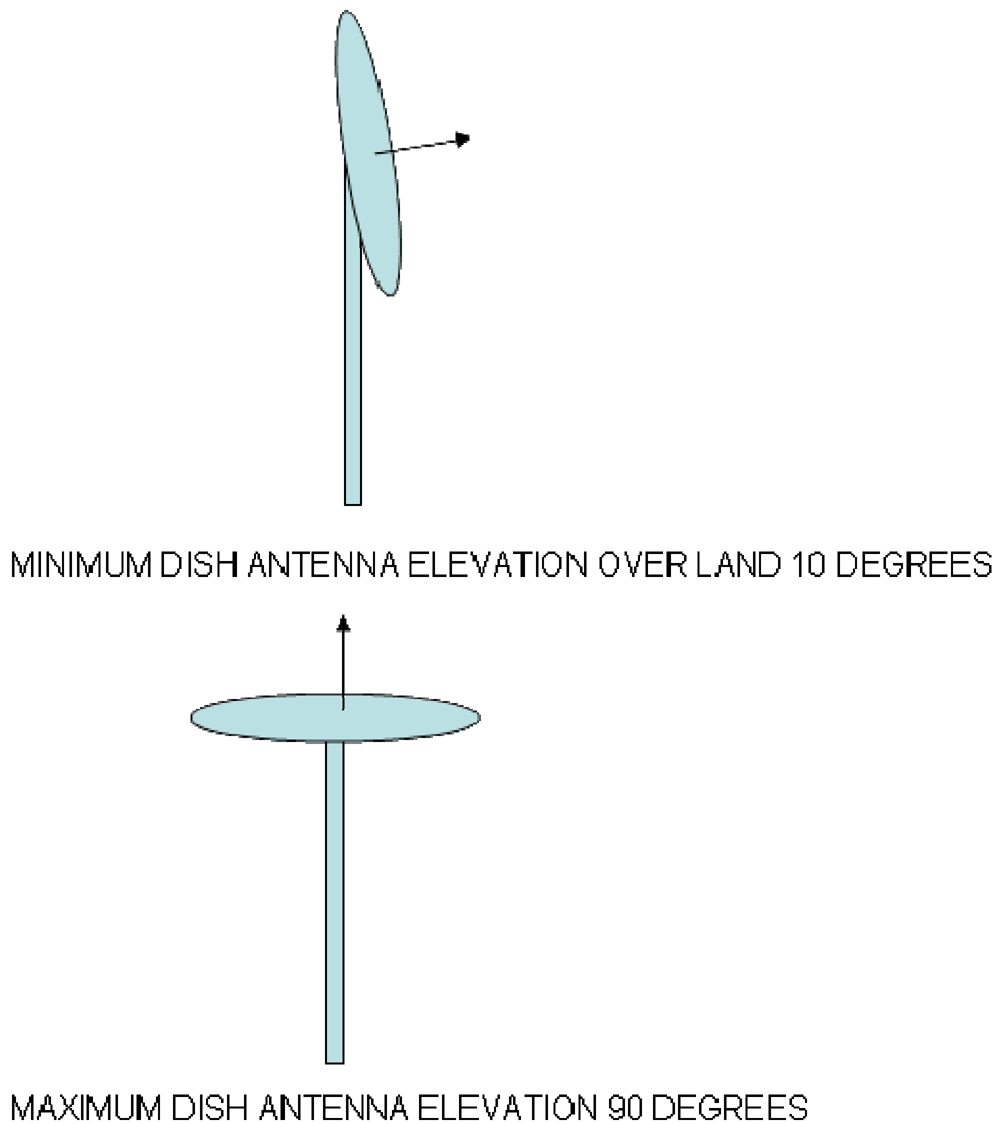

Figure 6. Minimum & Maximum Elevations

4. Enclosure

The outdoor enclosure has a single door with two lockable handles, which both latch. The enclosure is 24” wide, 20” deep, and 30” high. DDB is the manufacturer and model PSOD-302429FT was purchased. The purpose of the outdoor enclosure is to protect the computer, controller, frequency synthesizer, uninterruptible power supply (UPS), and transceiver card from the elements. It is located as close as possible to the feed horn, on the antenna base, to minimize the line losses between the feed horn and the

transceiver card. The UPS depicted in Figure 3 will need to power all of the equipment in the enclosure and the azimuth and elevation motors for twenty minutes. None of the satellite passes will be longer than twenty minutes, so if the AC power is lost at the beginning of a satellite pass the system will still have enough battery power to track and communicate through the entire pass.

THIS PAGE INTENTIONALLY LEFT BLANK

III. NPSAT1 LINK BUDGET

A. COMMUNICATIONS LINK BUDGET

This chapter seeks to clarify the calculations used for the generation of the link budget. The link budget is a cumulative calculation of transmitter to receiver gains and losses which determines if the link is strong enough for reliable communications. Bidirectional communications mean that this link budget must be calculated from the satellite to the ground receiver and from the ground receiver to the satellite.

The short form of the uplink budget to NPSAT1 is depicted in Table 1, and a carrier to thermal noise ratio is calculated using the format in Gordon and Morgan's Table 2.5 (1993) (p. 44).

Receiving earth station location: Monterey, CA
Uplink frequency f_u: 1.76757 GHz
Transmit earth station antenna diameter: 3.048 m
Satellite: NPSAT1 Uplink beam: 4 degee spot beam

Parameter	Sign	Value	Units	Section
Earth Station				
Power at the antenna for $P^* = 5$ W/carrier		6.99	dBW	
Transmit antenna gain G	+	32.43	dBi	4.a.
Earth station EIRP		39.42	dBW	13.
Earth to Satellite				
Free space path loss L for S_u = 1840 km	-	162.69	dB	11.
Satellite				
Satellite G/Ts,u	+	-21.6	dBi/K	
Carrier/thermal noise Cu/Tu		-144.87	dBW/K	
1/k (k = Boltzmann's constant)	+	228.6	dB(W/Hz K)$^{-1}$	
Cu/kTu		83.731	dBHz	

Table 1. NPSAT1 Uplink Budget, Short Form

This short format has section numbers which correspond to the calculations that follow in this chapter. The drawback of this short format is that it does not include losses for the pointing errors of both the ground and spacecraft antennas. The short form is useful though because the high carrier to thermal noise value of 87.73 dB Hz indicates that the link should have adequate strength. This value will be compared with the carrier to thermal noise from the long uplink budget. The long link budget is a more detailed spreadsheet that is developed with information from the calculations that follow in this chapter.

1. Margin

How much margin is sufficient for reliable communications? The guidance given by Space Mission Analysis and Design (SMAD) edited by Larson & Wertz (1999) is to "Adjust the input parameters until the margin is at least 3 dB greater than the estimate value for rain degradation, depending on confidence in the parameter estimates." (p. 568). Rainfall is sparse in Monterey and outages during the handful of days annually with heavy precipitation are acceptable. Since Gaussian Minimum Shift Keying is being used a value of 9.6 dB is extracted from Larson and Wertz's Table 13-11 as the minimum received energy per bit over noise-density (E_b/N_o) (p 562).

2. Slant Range

The slant range is calculated by knowing the maximum altitude of NPSAT1 and the minimum elevation of the ground antenna. Presently the launch parameters of NPSAT1 are unknown so H = 560 km will be used because it was the maximum altitude of the Orbital Express Launch. The 10 degree minimum elevation that is imposed on the antenna to reduce interference from and to ground stations is also used. Work began with equation (5-24) from Larson & Wertz (1999) (p.113).

$$\sin \rho = \cos \lambda_0 = \frac{R_E}{R_E + H} \text{ ; Or} \qquad \text{[Equation 3-1]}$$

$$\sin \rho = \frac{R_E}{R_E + H} \text{ ; So}$$

$$\sin\ \rho = \frac{6371.0003km}{6371.0003km + 560km} \therefore \sin\ \rho = 0.919204$$

$$\therefore \rho = 66.8099^\circ$$

Using Equation (5-26b) from Larson and Wertz (p. 113) …

$$\sin\eta = \cos\varepsilon \sin\rho$$

$$\sin\eta = \cos(10^\circ)0.919204 \quad \text{[Equation 3-2]}$$

$$\sin\eta = 0.905239$$

$$\therefore \eta = 64.8555^\circ$$

Using equation (5-27) from Larson and Wertz (p. 113)…

$$\eta + \lambda + \varepsilon = 90^\circ$$

$$\therefore 64.8555^\circ + \lambda + 10^\circ = 90^\circ \quad \text{[Equation 3-3]}$$

$$\therefore \lambda = 15.1445^\circ$$

Finally slant range, D, is solved with Larson and Wertz's equation (5-28) (p. 113).

$$D = R_E(\sin\lambda / \sin\eta)$$

$$D = 6371.0003km(\sin 15.1445^\circ / 0.905239) = 1838.69\ km \quad \text{[Equation 3-4]}$$

In the interest of simplicity, this is rounded up to 1840 km. Since this study began NPSAT1 missed the Orbital Express launch. Future launch opportunities include a Minotaur with an orbital altitude of between 600 and 700 km. For H=700 km the above calculations are performed to obtain D= 2155 km.

3. Bit Error Rate

The bit error rate (BER) is the probability of a single bit being erroneous. A probability of a bit error of 10^{-5} was chosen because that is a typical BER that is tolerable for telemetry and command signals. Using figure 13-9 of Larson & Wertz, with this probability of error, it is found that Gaussian Minimum Shift Keying (GMSK) yields a required energy per bit over noise ratio (E_b/N_o) of 9.6 dB (p. 561). With GMSK the spectrum utilization of 1 represents good use of spectrum. The bit rate for both uplink to and downlink from NPSAT1 is 115 kbps.

4. Antenna Gains

a. Ground Antenna

The aperture of the dish is 10 feet which is multiplied by 0.03048 to convert to 3.048 meters. The uplink gain is calculated using Gordon & Morgan's equation (6.5) (p. 140).

$$G = 20\log_{10} D + 20\log_{10} f + 10\log_{10}\eta + 20.4(dBi)$$
$$G = 20\log_{10}(3.048) + 20\log_{10}(1.76757) + 10\log_{10}(0.55) + 20.4(dBi) \text{ [Equation 3-5]}$$
$$G = 32.4(dBi)$$

Similarly, a downlink gain is calculated with the above equation using the 2.207 GHz downlink frequency and the result is 31.0 dB.

b. NPSAT1 Antennas

The gain of the patch antennas on NPSAT1 can be calculated using the same formula.

$$G = 20\log_{10} D + 20\log_{10} f + 10\log_{10}\eta + 20.4(dBi)$$
$$G = 20\log_{10}(0.0612) + 20\log_{10}(2.2073) + 10\log_{10}(0.90) + 20.4(dBi) \text{ [Equation 3-5]}$$
$$G = 2.6(dBi)$$

The receive elliptical patch antennas on NPSAT1 are slightly larger with an average diameter of 0.0764 meters. The receive frequency of 1.76757 GHz must also be used in the above equation to calculate a receive antenna gain of 0.4 dB.

These values were checked with a modified version of the antenna gain equation from Larson and Wertz (13-18b) (p. 555), and yielded identical values. It should be noted that *dBi* refers to isotropic decibels.

5. Pointing Error

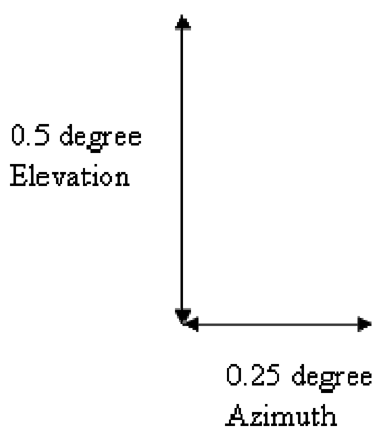

Figure 7. Controller Pointing Resolution

The pointing error of the ground antenna is more difficult to estimate. Controller tests revealed that the elevation drive only makes changes of one degree or more and that the azimuth rotor makes changes in half degree increments. The best pointing accuracy that can be hoped for is half of the hypotenuse of the pointing resolution, because the controller must wait for a 0.5 degree increase or decrease in elevation to change the

elevation of the dish and it waits for a 0.25 degree change in azimuth to bump the azimuth to the next closest azimuth increment. Consequently, the best possible pointing accuracy is the hypotenuse of the two values depicted in Figure 7, or 0.559017 degrees. That is the resolution of the M^2 controller but the software being tested does not command the controller to adjust the antenna unless there is a change in elevation or azimuth of a degree. The Nova software defaulted to 1.8 degrees of azimuth or elevation difference before commanding a change, but this was lowered to one degree. The hypotenuse of 1 degree of both azimuth and elevation is the square root of two or 1.41 degrees. This does not mean that the best pointing accuracy is 1.41 degrees because the Nova software can be set to lead the satellite. The Nova software allows setting of the rotator to lead the satellite in either time or degrees. By leading the satellite the hypotenuse of 1.41 is split which gives the best theoretical pointing accuracy of 0.7 degrees. Professor Smith of the Naval Academy uses the degree settings to lead an ascending portion by +1 degree and then changes the settings at zenith so that the elevation controller leads the satellite on the descending pass by -1 degree. The satellite is not really being led by the antenna. Instead the goal is to move the antenna in concert with the satellite passage. By setting a lead time of a few seconds the ground antenna adjusts while the satellite is moving so that it will not constantly be 1.41 degrees behind the satellite. Timing inaccuracies and direction errors reduce the 0.7 degree theoretical pointing accuracy but it is estimated that the total pointing error will be at least one degree. At elevations closer to zenith, above 50 degrees, the azimuth changes very quickly and the pointing accuracy decreases, because of the one second update rate of the single serial port connection. Because of this a 2 degree ground antenna pointing accuracy will be used in the link budget calculations. Final implementation of the controller may eliminate the use of the Nova software, and instead use a custom programmed antenna tracking routine. Still, the Nova software is an excellent program for testing of the ground antenna while programmers at NPS are focused on completing the NPSAT1 software. The pointing error of NPSAT1 towards nadir is estimated to be 10 degrees.

6. Efficiency

The ground antenna transmit feed efficiency of 55% is garnered from the range of typical values. Gordon and Morgan (1993) state "The typical range of antenna efficiency is 0.4 to 0.8 and a common approximation is 0.55" (p. 36). The same value is used for the receive efficiency of the antenna. NPSAT1 transmit and receive efficiencies of 90% were extracted from tests by Erel (2002) who depicts his results in his Figures 25 and 32 (p. 40, 44).

7. Noise Temperature

The ground receiver noise temperature is the combination of cosmic, galactic and troposphere noise as the antenna is pointed skyward. As elevation increases the troposheric sources of noise decrease so the minimum elevation of 10 degrees points the ground antenna above most of the noise radiation from the Earth. Gordon & Morgan's FIGURE 9.8 is entered with the 1.76 GHz transmit frequency and the minimum inclination of 10 degrees and yields a receiver noise temperature of 20 Kelvin (p. 206). This agrees with the summation of the maximum galactic noise temperature of 6 Kelvin from FIGURE 9.6 and the tropospheric noise temperature of 12 Kelvin from Figure 9.7 (20) Kelvin $\approx (12+6)$ Kelvin). This value assumes that the Sun and Moon are not in the side lobes or main lobe and that there are no terrestrial sources of interference in the back lobe or side lobes (p. 204,205).

The noise temperature that is used in the link budget is a total system noise temperature. It includes transmitter noise, noise from both antennas, and the receiver noise. Values are taken from Larson & Wertz's (1999) Table 13-10, and a brief description of their table is given (p. 558).

> Table 13-10 shows typical noise temperatures for satellite systems using uncooled receivers. When a narrow satellite-antenna beam looks at Earth, the uplink antenna noise temperature is the temperature of the Earth, about 290K. In the future improvements in design of low-noise amplifiers will reduce the receiver noise figures, especially at higher frequencies.

The system noise temperatures from the table are 135 Kelvin for the downlink and 614 Kelvin for the uplink.

8. Wavelength

The uplink frequency of 1.76757 GHz and the downlink frequency of 2.2073 GHz are easily converted to wavelengths by dividing the speed of light, 299,792,458 m/s, by them.

$$\begin{aligned}
&\lambda = c / f \\
&\lambda_U = (2999,792,458m / s) / (1767570000Hz) \\
&\lambda_D = (299,792,458m / 2207300000Hz) \\
&\lambda_U = 0.1696m, \lambda_D = 0.1358m
\end{aligned} \qquad \text{[Equation 3-6]}$$

9. Beam Width

The beam width of the ground antenna represents the cross section in degrees of the strongest part of the signal radiating to or from the antenna. It is the angle of the beam in degrees on the edge of which the signal experiences a 3 dB, or 50%, loss. Using equation 6.7 from Gordon & Morgan (1993) where *f* and *D* representing the frequency in GHz and diameter in meters of the antenna respectively 3.9 degrees is calculated for the uplink frequency (p. 143).

$$\begin{aligned}
&\theta_3 = 21/ fD(\text{deg}) \\
&\theta_3 = 21/(1.76757GHz)(3.048m) \\
&\theta_3 = 3.89787^{\circ}
\end{aligned} \qquad \text{[Equation 3-7]}$$

The receive beam width at the downlink frequency, 3.12178 degrees, is also calculated by inserting 2.207 GHz in the above equation.

Empirical data was used to determine the 70 degree half power beam width of the NPSAT1 hemispherical patch antennas. This value was averaged from Erel’s (2002) Figures 28, 29, 35 & 36 (p.42, 46).

10. Atmospheric and Rain Losses

Atmospheric and rain losses are difficult to determine at these relatively low frequencies, Gordon and Morgan (1993) state the following:

> The 1- to 10-GHz range is already used extensively by both terrestrial microwave and satellite services. Although the noise level and attenuation are lower than those at the higher frequencies, the potential for interference from terrestrial point-to-point services has limited the location of earth stations. (p. 179).

Interference is a greater concern at these frequencies because atmospheric and rain losses are negligible at 1.76 to 2.0 GHz. Half a decibel could be subtracted from the margin of the link budget spreadsheet to account for losses during periods of rain. Fortunately the school's proximity to the Monterey Bay allows an antenna site that can acquire the satellite over the ocean mitigating terrestrial interference. Placing the antenna on the tallest building on campus combined with the proposed minimum elevation over land of 10 degrees mitigates terrestrial interference on the descending half of satellite passes.

11. Free Space Path Loss

Free space path loss is the loss due to the slant range or distance between the transmitter and receiver. Slant range in kilometers and frequency in GHz are used for equation (2.30) from Gordon and Morgan (1993) to calculate a loss of 162.7 dB as is shown below (p. 39):

$$\begin{aligned} L &= 20\log_{10} S + 20\log_{10} f + 92.45(dB) \\ L &= 20\log_{10} 1840\,km + 20\log_{10} 1.76757GHz + 92.45(dB) \\ L &= (65.2964 + 4.94753 + 92.45)(dB) \\ L &= 162.694\,dB \end{aligned} \qquad \text{[Equation 3-8]}$$

The downlink path loss is almost identical to the uplink path loss because the only value that changes is the frequency resulting in a loss of 164.62 dB. The path loss will decrease as the slant range decreases and be at a minimum at the highest elevation during a pass.

12. Pointing Error Loss

Pointing error loss is related to both the pointing accuracy, *e*, and the half power beam width, θ_3. Larson & *Wertz* (1999) use θ (p. 556) where Gordon & Morgan (1993) use θ_3.

$$L_\theta = -12(e/\theta)^2 dB \; (13\text{–}21)$$
$$L_\theta = -12(2/3.89787)^2 \; dB \qquad \text{[Equation 3-9]}$$
$$L_\theta = -3.159268 \; dB$$

This calculation is also performed for the downlink to the ground antenna which has a narrower receive beam width due to the higher frequency and 4.809148 dB of loss is the result.

NPSAT1 antennas are more forgiving of pointing errors due to the omni directional properties of the patch antennas.

$$L_\theta = -12(10/72.0) \; dB \qquad \text{[Equation 3-9]}$$
$$L_\theta = -0.23 \; dB$$

13. Effective Isotropic Radiated Power

Effective Isotropic Radiated Power (EIRP) combines the gain of the antenna with its power. Gordon & Morgan (1993) define it as the sum of the antenna gain in dB and the transmitter power in dB (p. 36).

EIRP = $10\log_{10}P + G_t$ (dBW) (2.21) [Equation 3-10]
EIRP = 10 log $_{10}$*(5 Watts) + (32.4 Gain -4.16 Losses pointing & line)* (dBW)
EIRP = 35.27 (dBW)

Notice that the antenna pointing loss and line loss of one dB is subtracted from the antenna gain. An effective EIRP of 35.27 dB is obtained.

The same equation is used for NPSAT1's EIRP and because it has much less transmitting power (1 W) and antenna gain (2.56-0.23 dB) the result is 2.33 dB (remembering that 1 W = 0 dB). From 2.33 the line loss of 1 dB is subtracted leaving an effective EIRP of 1.33 dB

14. Propagation & Polarization Loss

Propagation loss is taken from Larson and Wertz's figure (13-10) from which a 0.3 dB loss is extracted (p. 563). It may include losses from transmitting through the plastic feed horn cover which is about the same thickness of a radome. In an example of a satellite using almost identical frequencies Larson and Wertz state "I would also add a loss of 0.3 dB to account for polarization mismatch for large ground antennas. Using a radome adds another 1 dB loss." (p. 568). For now, the loss of the plastic cover will be neglected because it may be removed during operation.

Polarization loss is attributed to the circular polarization of the signal being imperfectly matched with the polarization of the feed horn on the ground antenna or receive antenna on NPSAT1. Two feed horns are available, one for right hand circular polarization (RHCP) and the other for left hand circular polarization (LHCP). The feed horn used can be chosen based on the orientation or polarization of the satellite transmission to minimize polarization losses.

15. Link Budget

The long form of the link budget equation is given by Larson and Wertz at equation (13-13) in decibels as shown (p. 554).

$$E_b / N_o = P + L_l + G_t + L_{pr} + L_s + L_a + G_r + 228.6 - 10\log T_s - 10\log R \qquad \text{[Equation 3-11]}$$

P is the transmitter's effective power in dB. L_l is the line loss. G_t is transmit antenna gain less its pointing loss. L_{pr} is the pointing loss of the receive antenna. L_s is the free space path loss. L_a is the propagation and polarization loss. G_r is the receive antenna gain. T_s is the system noise temperature. R is the data rate. Table 2 summarizes the calculations in the link budget.

Analysis of the link budget in Table 2 shows that pointing accuracy of the ground antenna is critical. The downlink is lost when the pointing error is greater than 2.53 degrees, and the uplink is lost when the pointing error exceeds 4.19 degrees. The downlink is more sensitive to pointing error because of the smaller half power beam widths at the higher frequency of 2.207 GHz. This is corroborated by the operational experience of the sister ground antenna at the Naval Academy. The downlink from MidSTAR1 is lost before the uplink is lost.

Transmitter	**TM Down**	**CMD to NPSAT1**		**Section**, Reference and or Equation
Transmit Frequency (f) =	2.207	1.76757	Ghz	**II. A. 1.**
Power Budget Allocation in watts (Pt) =	12.05	56.18	*watts	25% and 75% of RF Pwr Bdgt, from "Power Budget" page
Transmitter Efficiency (ηdc) =	0.083	0.089		
Available Transmit Power (Pta) =	1.00015	5.00002	watts	
Transmitter Power in Decibels (Pt) =	0.000651393	6.989717415	dBw	
Transmitter Line Loss (Ll) =	-1	-1	dB	
Transmit Antenna Beamwidth (θbt) =	70	3.89787	deg	**III. A. 9.**
Transmit Antenna Pointing Error (θet) =	10	2	deg	**III. A. 5.**
Assumed Antenna Efficiency (η) =	0.9	0.55		**III. A. 6.** SMAD Figure of Merit p 553 = 0.55
Transmit Antenna Diameter (Dt) =	0.0612	3.048002523	m	**I. B. ; II. B. 4.**
PeakTransmit Antenna Gain (Gpt) =	2.563500201	32.44146578	dB	**III. A. 4. a. & b.** G = -159.59+20*LOG(Dt)+20*LOG(f~GHz)+10*LOG(η)
Transmit Antenna Pointing Loss (Lθt) =	-0.244897959	-3.159268491	dB	**III. A. 14.** Lθ = -12*(θet/θbt)^2
Transmit Antenna Gain (Gt) =	2.318602241	29.28219729	dB	Gpt+Lpt
Equiv. Isotropic Rad. Pwr. (EIRP) =	**1.319253634**	**35.2719147**	**dBw**	Pt+Ll+Gt
Spatial Geometry				
Sat Xmt Ant Max Cvg Ang (η°) =	0.610865238	0.034015333	rad	η° = 0.5*θbt
Earrth Central Angle (λ) =	0.079120784	0.003734866	rad	λ = 180-{η-acos[sin(η)/(Re/Ro)]+90}
ECA (λ) in degrees =	4.533287012	0.213992082	degrees	
Slant Range (S) =	1840	1840	km	**III. A. 2**. S = [(Ro-Re*cos(λ))^2 + (Re*sin(λ))^2]^.5
Coverage footprint Diameter =	2110.761286	125.1522865	km	plane geometry estimate
Coverage footprint in NM =	1139.720332	67.57685316	NM	
Power Flux Density (PFD) =	-134.9692015	-101.0165404	dB	PFD = EIRP/(4pS^2)
PFD/4kHz band =	-170.9898014	-137.0371403	dB	PFD/4000
Space (path) Loss (Ls) =	-164.6224031	-162.6938889	dB	**III. A. 11.** Ls = 147.55-20log(S~m)-20log(f~Hz)
Propagation & Polarization Loss (La) =	-0.3	-0.3	dB	**III. A. 15.** SMAD Table 13-13
Assumed Antenna Efficiency (η) =	0.55	0.9		**III. A. 6.** SMAD Figure of Merit p 553
Receiver Antenna Diameter (Dr) =	3.048	0.0764	m	
Peak Receiver Antenna Gain (Gpr) =	34.36997281	0.423026505	dB	**III. A. 4.** G = -159.59+20*LOG(Dt)+20*LOG(f~GHz)+10*LOG(η)
Receiver Antenna Beamwidth (θbr) =	3.121777879	70	deg	**III. A. 9.** θ = 21/(D*f)
Receiver Antenna Pointing Error (θer) =	2	10	*deg	**III. A. 5.**
Receiver Antenna Pointing Loss (Lθr) =	-4.925351613	-0.244897959	dB	**III. A. 12.** Lθ = -12*(θet/θbt)^2
Receiver Antenna Gain (Gr) =	29.4446212	0.178128545	dB	Gpr+Lpr
System Noise Temperature (Ts) =	135	614	K	**III. A. 7.** SMAD Table 13-10
Data Rate (R) =	1.15E+05	1.15E+05	bps	SMAD pg. 385, Table 11-19
Eb/No (1) =	17.60580401	22.32259427	dB	Eb/No = EIRP+Lpr+Ls+La+Gr+228.6-10LogTs-10LogR
Carrier-to-Noise Density Ratio (C/No) =	68.21278241	72.92957268	dB-Hz	C/No = Eb/No+ 10*logR
Bit Error Rate (BER) =	1.00E-05	1.00E-05	--------	**III. A. 3.**
Required Eb/No (2) =	9.6	9.6	dB	**III. A. 1.** SMAD Table 13-11
Implementation Loss (3) =	-2	-2	dB	Estimate
Margin =	**6.005804007**	**10.72259427**	**dB**	**III. A. 1.** (1)-(2)+(3)

Table 2. Link Budget

B. TEST LINK BUDGET

The test link budget is described here because it is the link that is used in the next chapter to find the optimal position of the feed horn and ensure that component gains and losses correspond to their expected values.

The measured line loss in the cable connecting the signal generator to the feed horn was -1.28 dB. The transmitting test antenna gain was calculated in an earlier test by pointing two test antennas at each other in the lab on a short five meter range. The test antenna gain was calculated as +6.93 dB with this empirical test. The initial test slant range, which is the distance between the transmit antenna and the aperture of the parabolic antenna, is 10 meters. Gordon & Morgan (1993) give us equation (2.30) (p. 39).

$$
\begin{aligned}
L &= 20\log_{10} S + 20\log_{10} f + 92.45(dB) \\
L &= 20\log_{10}(10/1000)km + 20\log_{10} 1.76757GHz + 92.45(dB) \\
L &= (-40 + 4.94753 + 92.45)(dB) \\
L &= 57.398\, dB
\end{aligned}
\qquad \text{[Equation 3-11]}
$$

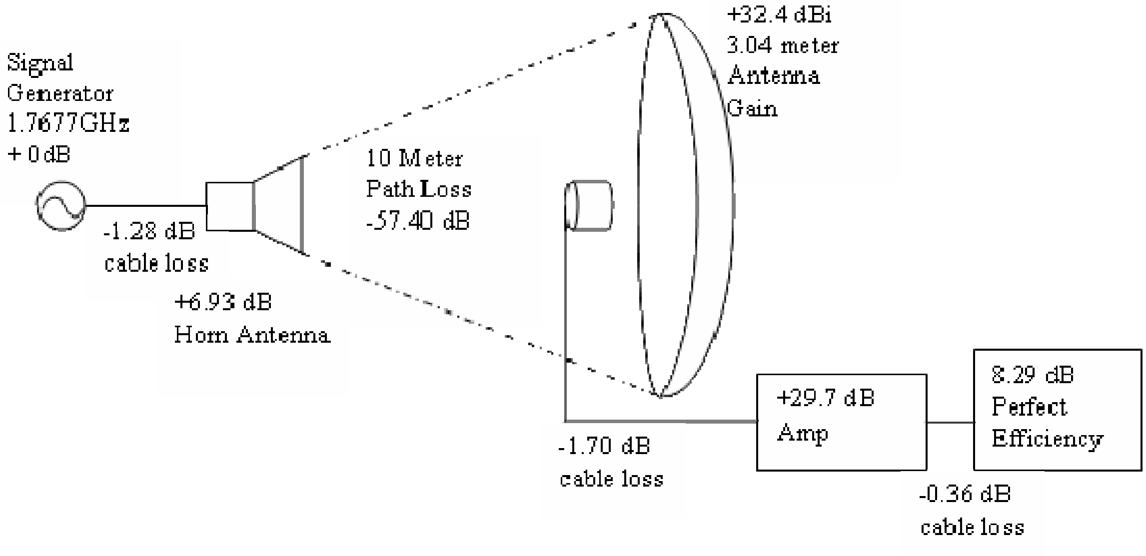

Figure 8. Test Link.

Since the measured value of 4.28 dB is 4.01 dB less than that shown in Figure 8 as the expected or “perfect efficiency” output of 8.29 dB, attenuation is probably causing a loss of 4.01 dB. Signal blockage caused by the clutter in the short range may be attenuating the signal resulting in a 4.01 dB loss. The test setup used had the parabolic antenna mounted on a plinth in the lab facing out the window toward the sidewalk. The test antenna horn was sited on a tripod on the sidewalk outside and pointed through the window at the parabolic antenna. Clutter consisted of the glass that the signal was sent through as well as the window frames and pillar that blocked the edges of the dish. Another possible source of the loss may be attributed to a near field test. The radio waves may not be parallel when they reach the parabolic reflector if this was a near field. The fact that the radio waves may not have been parallel means that their reflections were not as focused as they would be in a far field test. The far field distance for the same test horn antenna was calculated by Gokben (1996) as greater than or equal to 3.652 m (p. 18) using the downlink wavelength and the uplink wavelength for these tests. The longer wavelength of 0.1696 meters yields a lower calculated far field distance using equation (9-51) from Stutzman and Thiele (1998) (p. 413).

$$r_{ff} = \frac{2(D)^2}{\lambda} = \frac{2(0.4984m)^2}{0.1696m} = 2.93m \qquad \text{[Equation 3-12]}$$

The 10 meter range is above the far field range so losses must be attributed to blockage and hence attenuation of the signal. A test outside should be performed to check this theory. Using the same equation the for the 10 foot (3.048m) parabolic reflector a far field range of 110 meters is calculated.

$$r_{ff} = \frac{2(3.048m)^2}{0.1696m} = 109.6m \qquad \text{[Equation 3-12]}$$

So, a much longer range will be required to test transmissions from the ground antenna.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. TESTS, INSTALLATION, & CALIBRATION PROCEDURES

This chapter describes the calculations and test procedures for the setup of the ground antenna. It begins with the calculation and test of the feed horn placement and is followed by procedures for bore sighting the antenna. This chapter concludes with the description of the wind loading calculations. Some of the calibration procedures were not implemented yet and should be taken as recommendations.

A. FEED HORN

Using equation (6.1) from Gordon and Morgan (1993) gives the relationship used for calculating the focus of a parabola (p. 138). The calculated focus gives a starting point for the placement of the feed horn.

$$F = D\frac{D}{16d} \qquad \text{[Equation 3-13]}$$

Where D = the diameter of the dish and d = the depth of the dish. A 10 foot diameter was measured and a 21.25 inch depth, obtaining a 42.35 inches calculation for the focal point. The distance calculated is depicted in Figure 9 as the arrow drawn from the center of the reflector to the feed horn.

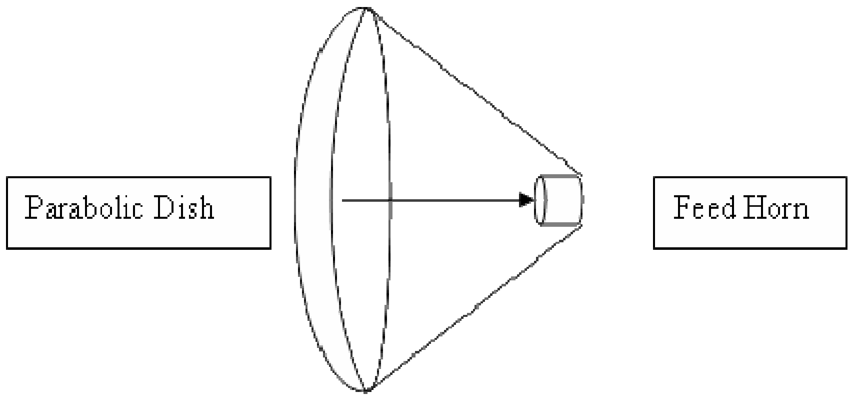

Figure 9. Feed Horn Placement

Other ways to check the focal point include placing a reflective mirror on the surface of the dish and using a laser pointer to confirm that light is reflected to the feed horn. The diameter of the feed horn mounting ring is six inches.

Tests were conducted to confirm the location of the feed horn by placing a transmitter on the sidewalk between the buildings to radiate to the dish inside the satellite lab. The feed horn was moved to find the spot with the most gain. 1767.56 MHz was the frequency used to transmit from the sidewalk through the window into the satellite laboratory. First the distance between the transmitting test horn and the dish was measured. The measurement of 10 meters was used to calculate the expected gain, as shown in Figure 8, of 8.29 dB.

Initial checks of the feed horn gain were made to determine whether the feed horn needed to be moved closer to the parabolic reflector or further away from it. Checks were made to ensure that the feed horn was perpendicular to the reflected signal from the dish antenna by shimming the feed horn. When it was shimmed to the left side gain improved

to -0.6 dBm. Where dBm are decibels of the power divided by one mW (1 x 10^{-6} Watts). Shimming the feed horn not only changes the angle of its aperture but also moves it closer to the reflector, so both sides were shimmed and the gain improved to -0.16 dBm. Realizing that the gain was improving, the feed horn was moved closer to the dish, and received signal strength improved to 0.46 dBm. When the feed horn was moved all the way in a signal of 1.12 dBm was measured. The original feed horn mounting ring did not permit the feed horn to be moved closer to the dish, but it appeared that the gain would improve if it could be further adjusted. At this point, it was apparent that the feed horn mounting plate would have to be re-machined so that the feed horn could be mounted closer to the parabolic reflector.

Tests began the next day with the feed horn mount bolted to the inside of the support arms allowing feed horn adjustment closer to the reflector as shown in Figure 10.

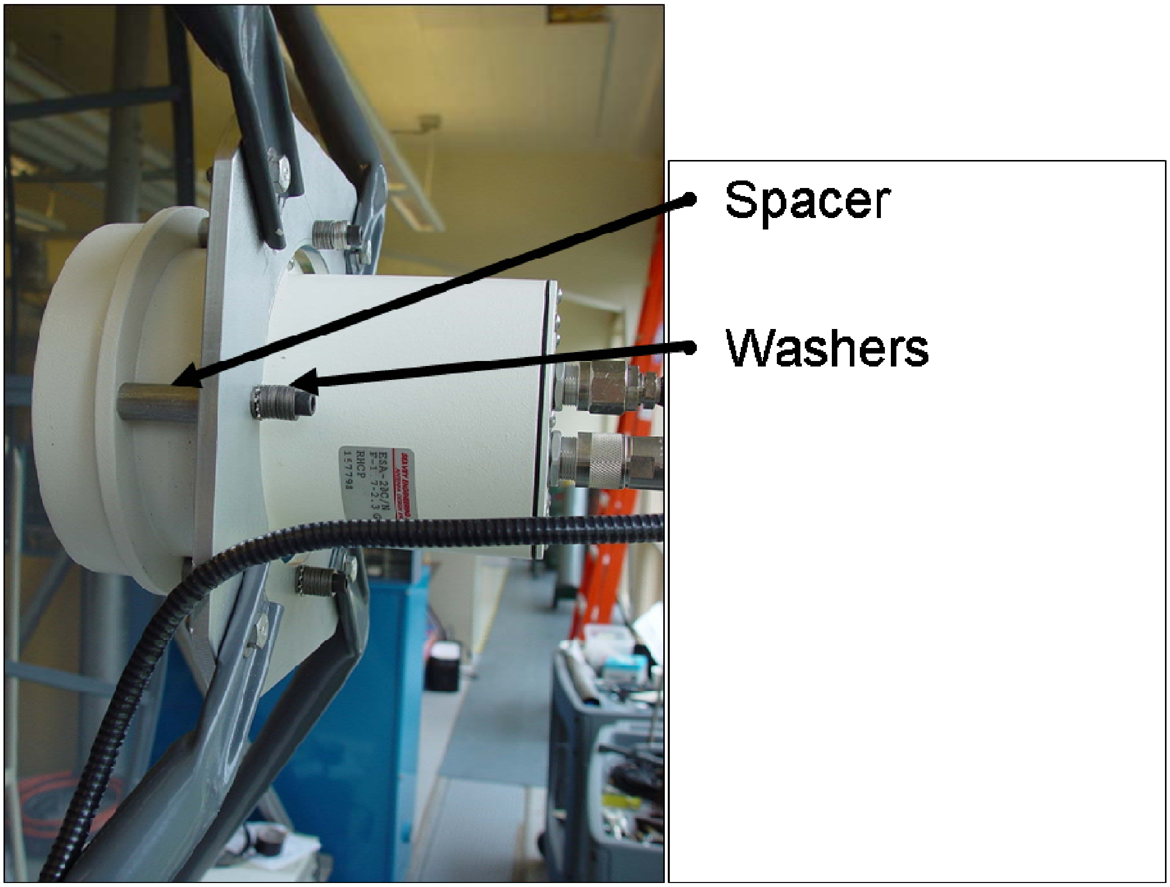

Figure 10. Feed Horn Mounted Inside Support Arms

The washers shown in Figure 10 were abandoned and replaced with springs for faster adjustment. The first test with new feed horn position immediately yielded 4.2 dBm. When the feed horn was moved out to the edge of the mount a signal of 3.8 dBm was observed. The feed horn was then moved half way back to the starting point with shims and tape and an output of 3.99 dBm was obtained. This indicated that the signal gain increased toward the starting point. When the feed horn was moved in further with smaller nuts and tape, a 4.01 dBm signal was observed. At that point it was decided to again modify the mounting bracket to allow further adjustment toward the reflector.

On May 8, 2007 the feed horn mounting plate was redesigned by Glenn Harrell. Excess aluminum was machined away from the new plate to minimize its blockage of the reflector aperture. When the new machined mounting ring for feed horn was installed the first reading was 4.2 dBm. Table 3 depicts the sequence of the tests on the installed feed horn mounting plate.

Step	Direction Moved	Signal
1		4.2 dBm
2	In	4.1 dBm
3	All the way out	4.09 dBm
4	In to 5/16 inches from plate	3.89 dBm
5	In to 3/8 inches from plate	3.93 dBm
6	In to 5/8 inches from plate	4.08 dBm
7	In to ¾ inches from plate	4.2 dBm
8	In to 7/8 inches from plate	4.22 dBm
9	In to 1 inch from plate	4.25 dBm
10	In to 1 & 1/16 inch from plate	4.19 dBm
11	Back to 1 inch from plate	4.25 dBm

Table 3. Feed horn position final tests

Conveniently, the rubber gasket on the feed horn was aligned flush with the back of the mount at this optimal position. The distance between the center of the parabolic reflector and the feed horn was measured as 43 & 7/8” +/- 1/32”. A graphical depiction of the output signal at the best measured signal position is shown in Figure 11.

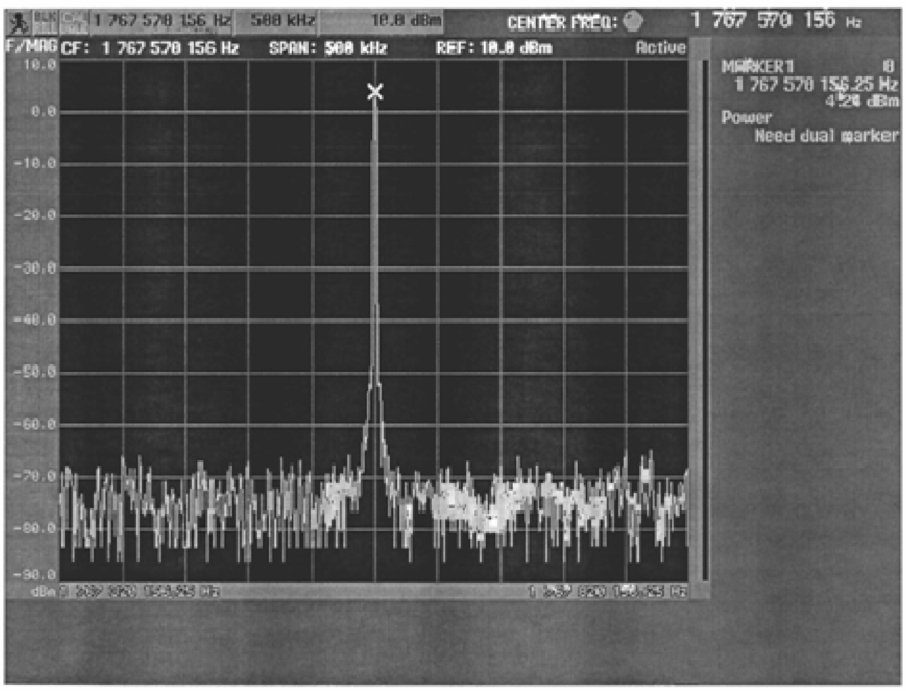

Figure 11. Feed Horn Signal Measurement

B. TEST EQUIPMENT

Two standard gain signal horns
Engineering Development Units using the same transmitters as those in NPSAT1
Cellular telephones
Vehicle
EDU Battery Supply
Binoculars
Handheld GPS
Antenna
Spectrum Analyzer
Surveyor’s Tripod
Maps USGS
Google Earth

C. PROCEDURES

1. Sources of Error

Sources of pointing error for the link between ground station and satellite, and methods of mitigating them are discussed in this section because the bore sighting procedures that are described later in this chapter minimize the largest source of error.

a. Timing Errors

If the computer time is wrong then it will track the satellite either early or late. This is eliminated at the Naval Academy because their computer time synchronizes with GPS time over the internet. By using either the internet or by using a dedicated GPS receiver to bring a time value directly into the computer through a serial port connection timing errors will be minimized.

b. Satellite Orbital Ephemeris

The satellite orbital parameters and the time associated with its location in the orbit is defined in the orbital ephemeris. Ephemeris is automatically downloaded with

the Nova software on a daily basis from http://www.space-track.org/perl/login.pl . MidSTAR1 was loaded in “My Favorites” and the NOVA software was set to download updates from “My Favorites” on a daily basis. When NPSAT1 is launched it will have to be added to “My Favorites” on this website. The “Navy Fence” is a line of VHF transmitters and receivers that is now operated by the USAF to collect and update orbital ephemeris data on satellites as they traverse the 33rd parallel of the US.

c. *Antenna Location*

The Nova software has a Monterey, CA observer location as 36.60 degrees North and 121.88 degrees West. Two GPS readings of the antenna location were taken on 20 June 07 with a circular probable error of +/-10 meters. The following two positions were received and recorded:

$$Northing_1 = 36^\circ 35' 42.03''$$
$$Westing_1 = 121^\circ 52' 28.60''$$
$$Northing_2 = 36^\circ 35' 41.96''$$
$$Westing_2 = 121^\circ 52' 28.72''$$

Averaging these results in a location of 36.59499 degrees North and 121.87460 degrees West. Rounding and truncating these to two decimal places results in 36.59 degrees North and 121.97 degrees West. The least significant digit of both the latitude and longitude was different than the default for Monterey in the Nova database. A separate observer called Tower should be created to minimize the antenna location error. Nova does not include the elevation of the ground antenna but STK does, so STK should generate slightly more precise antenna pointing data by accounting for the height of the roof of Spanagel Hall above Monterey.

d. *Pointing Calibration*

With a spot beam smaller than four degrees any error in the calibration of the antenna will be added to the inherent pointing limitations, so the procedures listed in the sections below address how the antenna will be aligned to true azimuths and elevations. The Naval Academy uses the Sun to bore sight their antenna’s azimuth and

elevation before each pass but there are limitations to this approach. They experienced degraded azimuth calibration when the Sun is near zenith because the noise signal from the Sun is less sensitive to changes in azimuth near zenith and more sensitive to changes in elevation. Conversely, when it is on the horizon the Sun is an excellent azimuth reference. In the Academy's use of the Sun a bullet camera was placed on the feed horn and pointed toward the parabolic reflector so the shadow of the feed horn could be viewed to check their alignment with the Sun. They also could site on the sun through cloud cover by dithering the antenna to the highest noise signal on a receiver. Another drawback of the Sun is that it is a moving target. The Naval Academy placed a transmitter at a known location on their roof to improve their calibration of azimuth while the Sun is high in the sky. A transmitter should also be placed on the roof of Spanagel Hall at a know direction and as far from the antenna as possible so that there is a known directional calibration point regardless of the sun's position.

2. Initial Assembly and Checkout

A standard gain antenna horn will be used to transmit through the glass to the antenna. The parabolic dish assembly area offered only a range though the glass window in the laboratory. At each phase of the test the expected loss will be calculated and compared to the actual loss. The antenna will then be dithered to check for pointing accuracy.

3. Slewing Initial Checks

The remaining procedures in this section are proposed and were not completed at the time this thesis was published. The antenna will then be moved to the roof of Spanagel Hall where it will be slewed to a known point on the roof of Spanagel Hall. Again, a standard gain horn will be used to transmit to the antenna.

4. Aiming Point Tests

a. Close Aiming Point

The standard gain antenna horn will be used to transmit to the antenna across the roof of Spanagel Hall. At this time the weatherproof enclosure will be integrated and testing of remote access of the computer controller in the rack over the Internet will begin.

b. Medium Aiming Point

The antenna will be slewed to a know point on Hilltop Field at the Presidio of Monterey. Although there is not a visual line of sight to this field there is a sufficient radio frequency signal through the forest between the two points. The standard gain horn will be used to transmit to the antenna and the spectrum analyzer will be used to check pointing accuracy. Voice communication between the aiming point and the Naval Postgraduate School's ground control can be established with cellular telephones.

c. Distant Aiming Point Tests

The antenna will be slewed to at least two distant know aiming points. These can include Mt. Toro, the lighthouse in Santa Cruz, and Freemont's Peak. Visible aiming points can also be used to align the antenna visually. The direction to the nearest smokestack at Moss Landing was measured as 20 degrees east of north and the antenna calibration can be checked by slewing it to that direction and visually sighting it. The Santa Cruz Mountains provide locations that are several miles away from the antenna, but high enough to permit line of sight radio signal reception. The ground antenna is calibrated by placing an L-band directional transmitter at two distant know points. The azimuths to the distant aiming points will be determined by using United States Geological Survey Maps and Global Positioning Receivers. Hiking may be required to the distant aiming points to orient and activate the directional transmitter. The directional transmitter will be visually sighted toward Naval Postgraduate School and a clear day after frontal passage should offer the best visibility for sighting the calibration antenna.

Optical enhancement, like binoculars and scopes, can be used to improve the sighting accuracy. The direction should be checked with a calculated direction to a known point. When the calibration antenna is sighted and powered the ground control team will point the antenna to the distant aiming point by loading the calculated direction and elevation. Reception signal strength will be measured and characterized to find the azimuth and elevation corresponding to the best signal reception. It is important to find a second location that has a different elevation than the first location to check the elevation and deflection slewing accuracy of the controller. This could be difficult because local terrain may present few options 10 degrees or more above Spanagel Hall. One approach may be to suppress the elevation of the elevation motor so that it can be tested through a range of motion on local terrain, and then reset it to an operational elevation after testing.

D. WINDPROOFING

Wind concerns were voiced by attendees of the 24 April,2007 briefing on the antenna. One constraint is that drilling into the roof of Spanagel Hall is not allowed, because its roof was recently weather sealed and is under warranty. Initially, the plan was to weld a custom ballast mount out of existing components but it was decided that buying commercially available Rhon antenna base was an easier solution. The Rohn ballast roof mount and short antenna base are depicted in Figures 12 and 13 respectively from Antenna Solutions and Control Inc. (1999). The azimuth rotator was mounted on the accessory shelf depicted in Figure 13 for an August 2007 demonstration of the assembled components. Attendees observed that the torque from azimuth motor was twisting the short base and causing the antenna to momentarily shake after a change in azimuth. Professor Panholzer suggested moving the accessory shelf to the bottom of the short base so that it attaches to the three mounts that are bolted to the ballast roof mount. This would mount the accessory shelf on a more rigid portion of the assembly and reduce the twisting of the antenna base. A much longer piece of pipe connecting the azimuth motor through the thrust bearing to the antenna will be required for this change.

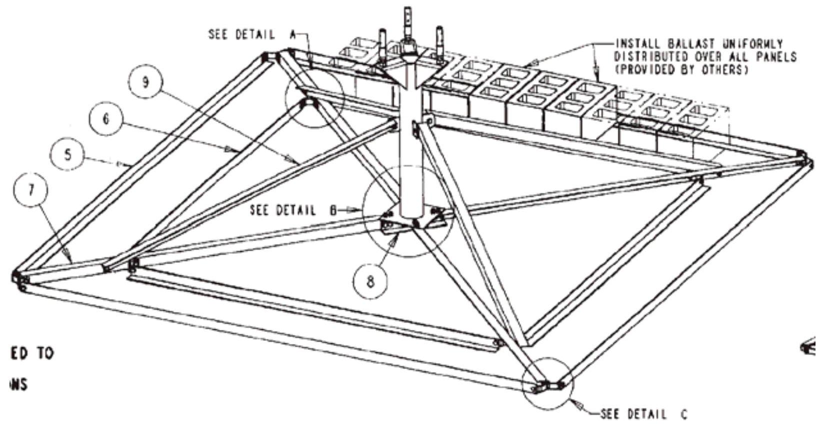

Figure 12. Ballast Roof Mount

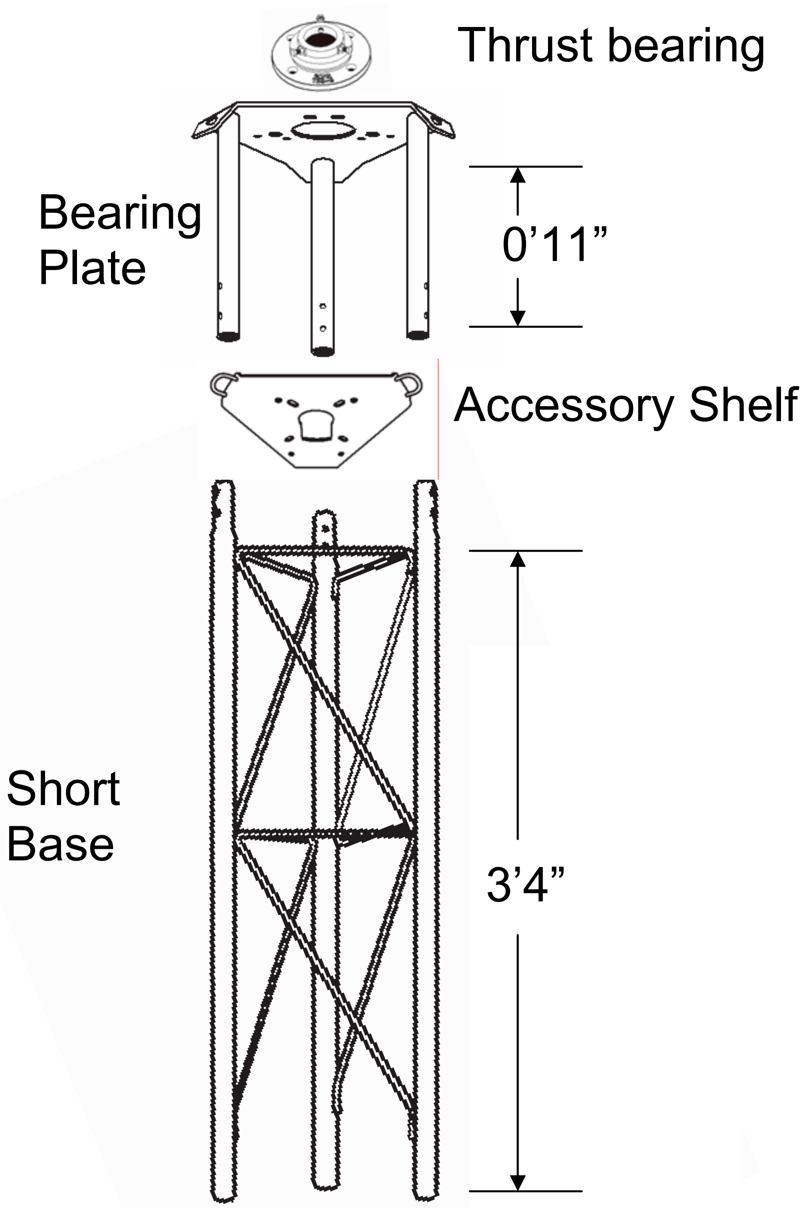

Figure 13. Antenna Base

Professor Panholzer asked for the weight of the antenna, because he was concerned about the load placed on the roof. The roof of Spanagel Hall is rated for 200 lbs per square foot. The disassembled antenna was weighed piecemeal. The elevation motor mount and dish ring mount assembly weighed 134 lbs. The antenna base assembly consisting of the components depicted in Figure 13 and the azimuth rotator weighs 79 lbs. The four antenna quadrants weighed 16.5 lbs and the middle plate weighed 2.95 lbs without mounting hardware so their total weight was rounded up to 20 lbs. The four feed horn arms weight five lbs with hardware. The feed horn and mounting ring four lbs. So the total weight of the antenna from the antenna base up is 237 lbs. The antenna weight is insignificant when compared to the weight of the ballast which will be discussed later in this section.

Assuming that the weight is evenly distributed across the 40 cinder blocks in the ballast roof mount which cover 38.4 square feet a 7,680 lbs load can be imposed on the ballast frame. This does not mean that that much ballast can be placed on the roof because the wind will add to the load of the ballast frame opposite the wind. An assumption is made that to account for wind loading the weight of the antenna and ballast should be half of the roof limit or 3,840 lbs. This is because at the instant before the wind topples the antenna the downward force on the roof opposite the wind, depicted in Figure 14, will equal approximately half the weight of the ballast.

Doctor Newman suggested that an anemometer be placed on the roof that is connected to the computer. A signal from the anemometer will elevate the dish in a safe of position of 90 degrees when the winds exceed a speed that is dangerous to the dish or the mount. This concept is depicted in Figures 14 and 15.

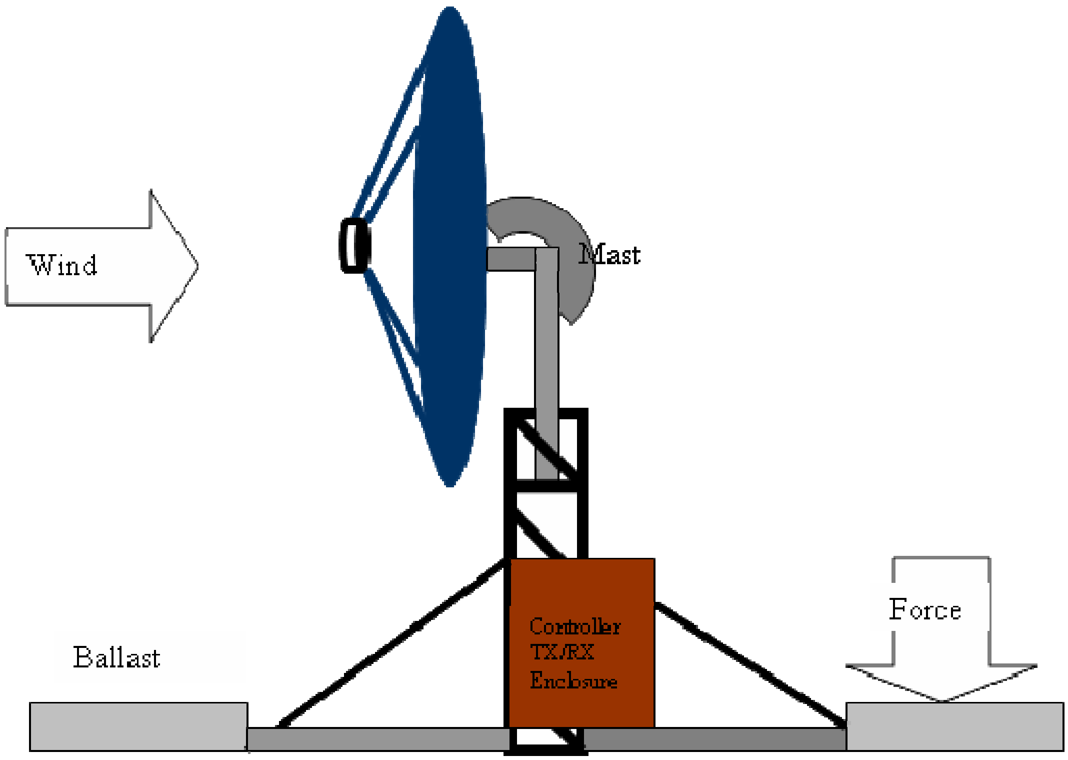

Figure 14. Wind Loading Perpendicular to Antenna Aperture

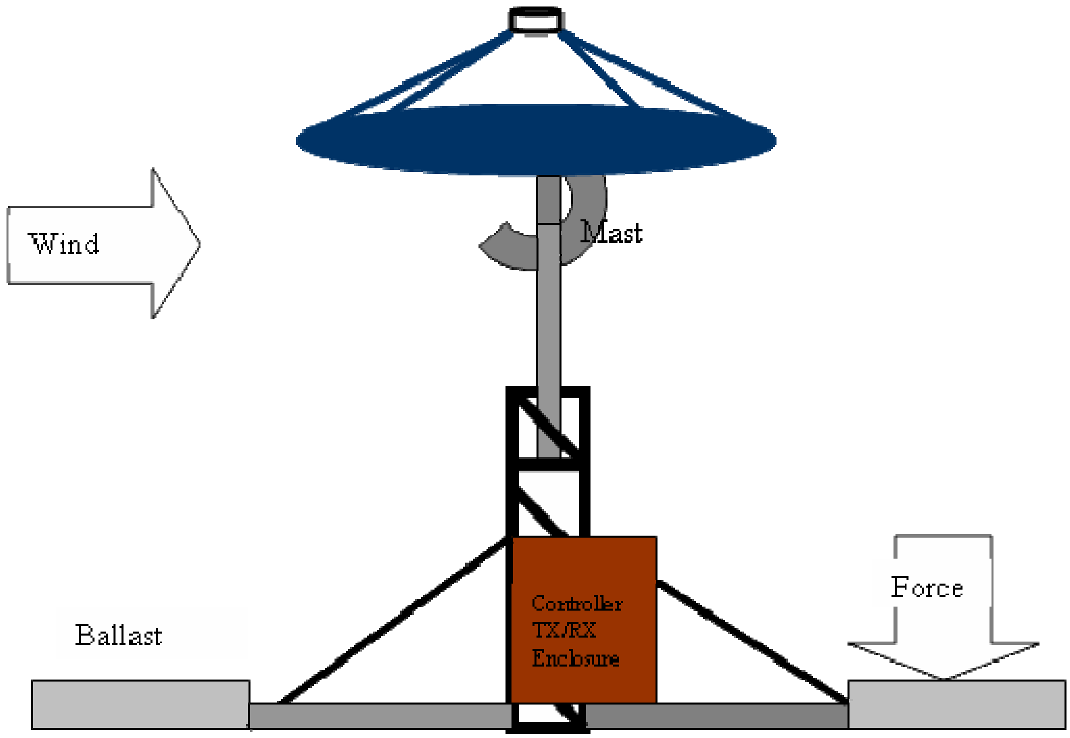

Figure 15. Wind Loading Parallel to Antenna Aperture

One concern of a longer mast is that the wind pushing on the dish has a longer moment arm so the platform may be less stable in severe winds. An advantage of the longer mast is that it would keep the dish above the PSOD-302420 outdoor enclosure. This outdoor enclosure is 30” high, 24” wide and 20” deep and can be pipe mounted on the side of the truss for the mast. The advantage of placing the transmitter and receiver enclosure close to the antenna is the reduction of line losses. It may be useful to estimate the force exerted on the mast since it is the weakest component in the assembly. Additionally, the force applied to the dish can be converted to a downward force on the opposing ballast frame to verify that roof loading tolerances are not exceeded. The final consideration is that the upwind ballast is not lifted by the force of the wind on the antenna.

Fortunately the Rohn mount that was purchased had data sheets available for wind loading. Bob Broadston said that a 150 mile per hour (130 knot) wind survival requirement was used for the roof of Spanagel Hall, because the fastest winds recorded in Monterey were 100 miles per hour. Assuming that the 10 foot dish is solid then it has an area of πR^2 or 78.54 square feet. Ricardo (2001) states, "Mesh dishes act as solid dishes at about fifty miles per hour though will still experience approximately 40% less force than a solid dish." Even if that area is reduced by 40%, because it is a mesh dish, the area of 47.12 square feet is off the table that Rhon provides for their mount. 18 square feet is the largest antenna area shown on Table 4 and that is only 38% of the calculated maximum area of the antenna. Wind survival is calculated based on attaching an anemometer to the box which elevates the dish to 90 degrees when the wind achieves 30 nautical miles per hour (knots) or more. The depth of the dish is 21.25 inches, and that is used for this calculation. The area of the dish when elevated to 90 degrees is the area of the crescent shape exposed to the wind. Adding ¾ of an inch to the depth to take into account the depth of the ribbing that gives the dish its strength increases the dish depth to 22 inches. Using an equation from Beer & Johnston for the area of a parabola where h = 22 inches and a = 60 inches. The area of the parabola = $4ah/3$ = 12.2 ft^2 (p. 175).

Calculating the weight of the ballast is done by multiplying the weight of each cinder block by the number of blocks. A high density cinder block from the existing mounts on the roof was weighed. The empty weight was 34.5 lbs. Since each cage holds ten cinder blocks on each of it, four sides could be loaded with 345 lbs per side or 1380 lbs with a single layer of these blocks. The dimensions of the blocks are 8" by 8" by 16" and cement was poured in the cinder block holes to fabricate heavier solid blocks. This increased the individual weight of each cinder block to 60 lbs. Forty of these cinder blocks weigh 2400 lbs. The sum of the calculated edge of dish area of 12.2 ft^2 plus the area of the box steel section, which acts as the middle connector between the elevation mechanism and the antenna mounting ring, gives the total area. The box section "sail" area of up to 1.63 ft^2 plus the area of the stowed dish gives a total area of 13.83 ft^2. That is rounded up to 14 ft^2 to account for the areas of the elevation motor and ring. Table 4, from Antenna Systems and Solutions Inc. (1999) is entered in the effective

projected area row of 14 ft^2 and the entry weight of 2400 lbs is interpolated between the ballast column values of 2250 lbs and 2500 lbs (p. MS-4). Following that to the wind velocity, Vs, for one section at both 2250 and 2500 lbs wind speeds of 158 and 166 mph are extracted. Simple linear interpolation is used to calculate a wind velocity, Vs, of 162.8 mph, which is rounded down to 162 mph. Table 4 is the manufacturer's table for loading the antenna base. This table is being used conservatively because the short base that NPS procured is shorter than the section of 12.4' that is shown in the table. The measured height is 8.5' and even with the antenna fully elevated the top lip of the antenna will only be 10.3' high. The total weight of the 2400 lbs of ballast, the 237 lbs antenna assembly, and the 200 lbs ballast mount is 2,837 allowing approximately 1000 lbs of margin before the 3,840 lbs roof limit. The enclosure assembly weight is expected to be less than 100 lbs.

25G BRM ALLOWABLE ANTENNA AREAS

EFFECTIVE PROJECTED AREA (EPA) (FT^2)	BALLAST (LBS)	ZERO VELOCITY LOAD (PSF)	Vs ONE SECTION (MPH) h = 12.4 FT	Vs TWO SECTIONS (MPH) h = 22.4 FT	Vmax AT CENTROID OF PROJECTED AREA (MPH) CENTROID OF ANTENNA EPA h = 12.4 ft (1 sect)	h = 22.4 ft (2 sect)
8	500	5.0	91	76	72	48
	750	7.5	112	94	88	58
	1000	10.0	129	108	101	67
	1250	12.5	144	121	113	75
	1500	15.0	158	132	122	81
	1750	17.5	171	143	129	86
	2000	20.0	183	153	136	90
	2250	22.5	194	162	142	95
	2500	25.0	204	171	149	99
	2750	27.5	214	179	154	103
	3000	30.0	224	187	157	104
10	500	5.0	84	72	66	44
	750	7.5	103	89	80	54
	1000	10.0	119	102	93	63
	1250	12.5	133	114	104	70
	1500	15.0	146	125	112	76
	1750	17.5	158	135	118	80
	2000	20.0	169	145	124	84
	2250	22.5	179	153	130	88
	2500	25.0	189	162	136	92
	2750	27.5	198	169	141	95
	3000	30.0	207	177	144	97
12	500	5.0	79	69	61	42
	750	7.5	97	84	74	51
	1000	10.0	112	97	86	59
	1250	12.5	125	109	96	66
	1500	15.0	137	119	104	71
	1750	17.5	148	128	110	75
	2000	20.0	158	137	115	79
	2250	22.5	167	146	121	83
	2500	25.0	176	154	126	86
	2750	27.5	185	161	131	90
	3000	30.0	193	168	133	91

NO:	REV. DESCRIPTION:	DATE:	REV. BY:	CHKD. BY:	APPD. BY:

DRAWN BY: MSJ	DATE: 8/28/99	ROHN Industries, Inc.
CHECKED BY: HA	DATE: 8/30/99	
APP'D ENG: MSJ	DATE: 8/31/99	25G BRM ALLOWABLE
APP'D SALES:	DATE:	
FILE NUMBER: 41835DB		ANTENNA AREAS
DRAWING NUMBER:	A992094-2 OF 9	

25G BRM ALLOWABLE ANTENNA AREAS

EFFECTIVE PROJECTED AREA (EPA) (FT^2)	BALLAST (LBS)	ZERO VELOCITY LOAD (PSF)	Vs ONE SECTION (MPH) h = 12.4 FT	V's TWO SECTIONS (MPH) h = 22.4 FT	Vmax AT CENTROID OF PROJECTED AREA (MPH) CENTROID OF ANTENNA EPA	
					h = 12.4 ft (1 sect)	h = 22.4 ft (2 sect)
14	500	5.0	74	66	57	39
	750	7.5	91	80	70	48
	1000	10.0	105	93	80	56
	1250	12.5	117	104	90	62
	1500	15.0	129	114	97	67
	1750	17.5	139	123	103	71
	2000	20.0	149	131	108	75
	2250	22.5	158	139	113	78
	2500	25.0	166	147	118	81
	2750	27.5	174	154	123	85
	3000	30.0	182	161	125	86
16	500	5.0	70	63	54	37
	750	7.5	86	77	66	46
	1000	10.0	100	89	76	53
	1250	12.5	111	99	85	59
	1500	15.0	122	109	92	64
	1750	17.5	132	118	97	67
	2000	20.0	141	126	102	71
	2250	22.5	149	133	107	74
	2500	25.0	157	141	111	77
	2750	27.5	165	147	116	80
	3000	30.0	172	154	118	82
18	500	5.0	67	60	51	36
	750	7.5	82	74	62	44
	1000	10.0	95	86	72	50
	1250	12.5	106	96	81	56
	1500	15.0	116	105	87	61
	1750	17.5	126	113	92	64
	2000	20.0	134	121	97	68
	2250	22.5	142	128	101	71
	2500	25.0	150	135	106	74
	2750	27.5	157	142	110	77
	3000	30.0	164	148	112	78

NO:	REV. DESCRIPTION:	DATE:	REV.BY:	CHKD. BY:	APPD. BY:

DRAWN BY: MSJ	DATE: 8/28/99	**ROHN Industries, Inc.**
CHECKED BY: HA	DATE: 8/30/99	
APP'D ENG: MSJ	DATE: 8/31/99	**25G BRM ALLOWABLE**
APP'D SALES:	DATE:	
FILE NUMBER: 41835DB		**ANTENNA AREAS**
DRAWING NUMBER:	A992094-3 OF 9	

MS-4

Table 4. 25G BRM Allowable Antenna Areas.

THIS PAGE INTENTIONALLY LEFT BLANK

V. COMMUNICATIONS CONTINGENCIES

A. REDUNDANT GROUND STATIONS

The design of similar ground stations at both the Naval Academy and NPS enables either to act as a back up ground station if the ground station owning the satellite is inoperable. A comparison of the communication parameters of MidSTAR1 and NPSAT1 is shown below in Table 5.

MidSTAR1	NPSAT1
• Inclination = 46.02 ° overhead passes	• i = 57 ° ? minotaur 2009
• Frequencies 1.767GHz up/ 2.2022 GHz down	• 1.767 GHz up/2.027 GHz down
• Phase Modulation	• Frequency Modulation
• GMSK Gaussian Minimum Shift Keying	• GMSK
• 64 kbps up/100 kbps down	• 115.2 kbps
• Beacon with some Telemetry every 4 minutes	• Beacon only in fail mode

Table 5. Communications Parameters Comparison

B. NPSAT1 CONTROL

What happens if communications with NPSAT1 are lost? NPSAT1 uses a software controlled radio, so one possibility is for the satellite to step down its bandwidth if communications are spotty. NPSAT1's default bandwidth is 115.2 kbps as shown in Table 5 and this number drives the speed at which data is transferred to and from the spacecraft. Dynamically lowering the bandwidth from 115.2 kbps increases the margin in the link budget, but lowers the data rate. This is analogous to speaking more slowly on a cellular telephone if the person on the other end cannot understand what is being said. Because the coding of the field programmable gate array (FPGA) that controls communications has not been finalized the exact band width that will be used, if there are communications problems, has yet to be determined.

Another point of failure for communications with NPSAT1 is the on/off routine for the antennas which is based on calculations of when the satellite is over the Monterey, CA area. To conserve electricity the satellite receiver is only activated when its GPS and orbit propagator predict it to be over the Monterey, CA area. If the NPSAT1 controller reboots and does not have orbit position awareness then the "No Nav" branch in Figure 16 is followed. This causes the receive antenna to turn on for thirty seconds of every two minute period. The receiver remains on if the ground antenna is successfully transmitting to it. If the onboard GPS has failed, then the priority after a reboot should be to upload new predictions to NPSAT1 making it easier to acquire with the ground antenna. This process is displayed in the block diagram in Figure 16.

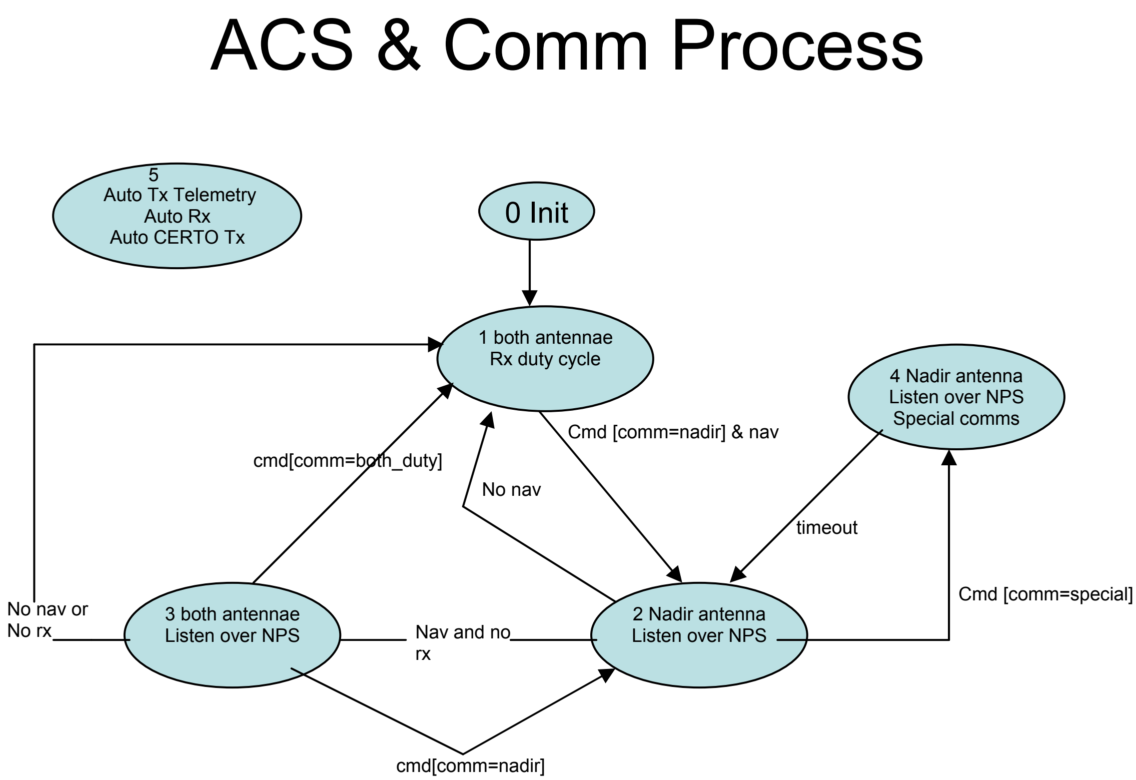

Figure 16. NPSAT1 Communications Contingencies.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. CONCLUSION AND RECOMMENDATIONS

The link budget proves that the downlink is very sensitive to the pointing accuracy of the ground antenna. The single most important conclusion of this work is that a more accurate ground antenna pointing control scheme should be implemented before NPSAT1 is launched. It is no surprise that the link with MidSTAR is intermittent, because the antenna controller and software at the Naval Academy is identical to that tested here. Pointing accuracy could be improved by splitting the elevation control and azimuth control with the separate elevation and azimuth controllers. This would facilitate two individual 9600 baud RS-232 serial connections. Dr. Michael Owen (personal communication, July 19, 2007) of Northern Lights Software estimated that their Nova software could be modified to support two separate controllers with eight hours of their programming time which was quoted at a rate of $100 an hour. Alternatively, use of a high-fidelity SGP4 algorithm would allow more precise control of the antenna rotors with in house configuration of custom software.

The large parabolic ground segment dish antenna can be installed on a commercial mount when wind speed data sent to the computer has the controller place the dish in a safe configuration.

Software radio features of both NPSAT1 and the demodulator card in the ground computer enhance our capabilities. The software controlled radio in NPSAT1 allows it to lower the data rate as a communications contingency and the ground computer software radio card compensates for Doppler shift with AFC. The PCI software radio card on order will allow communications with both MidSTAR1 and NPSAT1. Frequency modulation (FM) is employed on NPSAT1 but the MidSTAR1 uses phase modulation (PM). Fortunately, the PCI radio card that was ordered can demodulate either FM or PM.

The ability to track the beacon on MidSTAR1 will prove that the antenna control system will function with NPSAT1. Another recommendation is to conduct far field tests with the parabolic dish antenna to obtain an empirical value for its efficiency which could be used in the link budget instead of the estimate.

A follow on study should be completed to detail ground segment operation. This would establish the procedures for sending commands and receiving telemetry from NPSAT1. MidSTAR should be used, if it is still operational, to test sending commands and receiving telemetry from a satellite. Work with MidSTAR1 could be used as a basis for the future operation of the NPSAT1 ground segment.

LIST OF REFERENCES

Antenna Systems and Solutions Inc. *25BRGM Assembly Drawing; 25BRGM Ballast Chart.* (1999). Retrieved 1 September 2007 from: http://www.antennasystems.com/rohn/mounts.html .

Erel, Mahmut. *Design of Microstrip Patch Antenna for the NPSAT1*, (2002) Monterey, CA: Naval Postgraduate School.

Gokben, Ilahn. *Prototype Fabrication and Measurements of Uplink and Downlink Microstrip Patch Antennas for NPSAT-1*, (2003) Monterey, CA: Naval Postgraduate School.

Gordon, Gary; Morgan, Walter. *Principles of Communications Satellite*, (1993) Hoboken, NJ: John Wiley & Sons, Inc.

Larson, Wiley; Wertz, James. *Space Mission Analysis and Design* Third Edition, (1999) El Segundo, CA: Microcosm Press.

L3 Communications Telemetry-East (2004). *Technical Bulletin PCI-2070.* Retrieved 31 August 2007 from http://www.l-3com.com/TE/PDF/PCI-2070.pdf .

Reed, Jeffrey H. *Software Radio a Modern Approach to Radio Engineering*, (2002) Upper Saddle River, NJ: Prentice Hall PTR.

Ricardo, R. *Installation Discussion* (2001) Retrieved 1 September 2007 from: http://www.geo-orbit.org/sizepgs/grndpole.html.

Sakoda, Daniel; Horning, James. *Overview of the NPS Spacecraft Architecture and Technology Demonstration Satellite, NPSAT1* (2002) Proceedings of the 16th Annual AIAA/USU Conference on Small Satellites. Logan, Utah.

THIS PAGE INTENTIONALLY LEFT BLANK

BIGLIOGRAPHY

Meeks, M. Ball, John. Hull, Anthony. *The Pointing Calibration of the Haystack Antenna*, November (1968) IEEE Transactions on Antennas and Propagation, VOL. AP-16 NO.6.

Rodin, A. Sekido. M. *Pulsar VLBI Observations*, (2002) Proceedings of the 6th European VLBI Network Symposium. Bonn, Germany.

Tomasi, Wayne. *Electronic Communications Systems Fundamental Through Advanced*, fifth edition, (2004), Upper Saddle River, NJ: Pearson Education, Inc.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Professor Rudolf Panholzer
   Naval Postgraduate School
   Monterey, California

4. Professor William Smith
   U. S. Naval Academy Physics Department
   Annapolis, Maryland

5. Daniel Sakoda
   Naval Postgraduate School
   Monterey, California

6. James Horning
   Naval Postgraduate School
   Monterey, California

7. David Rigmaiden
   Naval Postgraduate School
   Monterey, California

8. Professor Alan Ross
   Naval Postgraduate School
   Monterey, California

9. Ronald Aikins
   Naval Postgraduate School
   Monterey, California